# Investigation of Plasma Spray Coatings as an Alternative to Hard Chrome Plating on Internal Surfaces

## SERDP Project WP-1151 Final Report


**Keith O. Legg**
***Rowan Technology Group***
***Libertyville, IL***

**Bruce D. Sartwell**
***Naval Research Laboratory***
***Washington, DC***

**Jean-Gabriel Legoux**
***National Research Council Canada – Industrial Materials Institute***
***Boucherville, Canada***

**Montia Nestler and Christopher Dambra**
***Sulzer-Metco***
***Westbury, NY***

**Daming Wang and John Quets**
***Praxair Surface Technologies***
***Indianapolis, IN***

**Paul Natishan**
***Naval Research Laboratory***
***Washington, DC***

**Philip Bretz**
***Metcut Research Inc.***
***Cincinnati, OH***

**Jon Devereaux**
***Naval Air Depot***
***Jacksonville, FL***



**June 20, 2006**


**Approved for public release; distribution is unlimited**

# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*



**1. REPORT DATE** *(DD-MM-YYYY)*
14-09-2006

**2. REPORT TYPE**
Memorandum Report

**3. DATES COVERED** *(From - To)*
October 2000 - June 2006

**4. TITLE AND SUBTITLE**

Investigation of Plasma Spray Coatings as an Alternative to Hard Chrome Plating on Internal Surfaces

**5a. CONTRACT NUMBER**

**5b. GRANT NUMBER**

**5c. PROGRAM ELEMENT NUMBER**
30603716D8Z

**5d. PROJECT NUMBER**
WP-1151

**5e. TASK NUMBER**

**5f. WORK UNIT NUMBER**

**6. AUTHOR(S)**

Keith O. Legg,* Bruce D. Sartwell, Jean-Gabriel Legoux,[#] Montia Nestler,** Christopher Dambra,** Daming Wang,*** John Quets,*** Paul Natishan, Philip Bretz,‡ and Jon Devereaux†

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**

Naval Research Laboratory
Code 6170
4555 Overlook Avenue, SW
Washington, DC 20375-5320

**8. PERFORMING ORGANIZATION REPORT NUMBER**

NRL/MR/6170--06-8987

**9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)**

Strategic Environmental Research and Development Program
901 North Stuart Street, Suite 303
Arlington, VA 22203

**10. SPONSOR / MONITOR'S ACRONYM(S)**

SERDP

**11. SPONSOR / MONITOR'S REPORT NUMBER(S)**

WP-1151-FR

**12. DISTRIBUTION / AVAILABILITY STATEMENT**

Approved for public release; distribution is unlimited.

**13. SUPPLEMENTARY NOTES**

*Rowan Technology Group, Libertyville, IL; [#]National Research Council Canada, Boucherville, Canada; **Sulzer-Metco, Westbury, NY; ***Praxair Surface Technologies, Indianapolis, IN; ‡ Metcut Research Inc., Cincinnati, OH; †Naval Air Depot, Jacksonville, FL

**14. ABSTRACT**

Hard chromium electroplating is extensively used by aircraft manufacturers and military maintenance depots to provide wear and/or corrosion resistance or to restore dimensional tolerance to components. However, chrome plating utilizes hexavalent chromium, which is a highly toxic carcinogen, with increasingly stringent government regulations making it more expensive for DoD. This document constitutes the final report on an investigation of deposition of coatings using miniature plasma spray guns that could replace hard chromium on internal surfaces where conventional thermal spray technologies could not be used. The coatings investigated included WC/Co, WC/Co with an Ni self-fluxing alloy, WC/CrC/Ni, and Tribaloy 400. Materials tests showed that all of the carbide coatings demonstrated sliding and abrasive wear performance equivalent or superior to hard chromium. Electrochemical corrosion measurements generally showed inferior corrosion performance. A cost analysis indicated that plasma spraying was comparable to hard chromium using larger guns on cylindrical components with internal diameters of the order of 4" but for smaller diameters the plasma spray costs would be somewhat higher. However, turnaround times could be greatly reduced because of fewer process steps, including the elimination of the 24-hour bakeout to remove hydrogen incorporated during chrome plating.

**15. SUBJECT TERMS**

Thermal spray; Plasma spray; Hard chromium plating; Tungsten carbide coatings; Fatigue; Wear; Corrosion

| 16. SECURITY CLASSIFICATION OF: a. REPORT | b. ABSTRACT | c. THIS PAGE | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| Unclassified | Unclassified | Unclassified | UL | 180 | Bruce D. Sartwell |

**19b. TELEPHONE NUMBER** *(include area code)*
(202) 767-0722

# Executive Summary

This program was aimed at developing the plasma spray method for ID chrome replacement in items such as hydraulic actuators and landing gear.

The following six coating materials were tested:

1. Baseline hard chrome plate deposited by NADEP Jacksonville.
2. WC-12Co made with fused and crushed powder (Sulzer Metco Diamalloy 2003), which is the only simple WC cermet that appears capable of being plasma sprayed with porosity in the 6% range. Because it has the largest proportion of WC of the coatings under examination, it is likely to offer the best wear resistance. However, it has the lowest percentage of binder and hence a relatively low fracture strength, making it prone to cracking. It may be the best option for utility actuators that experience side loads or excessive ID wear.
3. WC-Co mixed with Ni self-fluxing alloy, Sulzer Metco Diamalloy 2002, formula 55% (88WC 12Co) 45%(66Ni 18Cr 7Fe 4Si 4B 1C). This is a softer material than WC-12Co, but had the lowest porosity of the plasma spray coatings in initial process development tests, as well as higher fracture strength as shown in 4-point bend testing. This combination of properties may make it ideal for most hydraulic system and landing gear IDs and piston heads, especially those used for carrier-based aircraft, which see very high loads.
4. The equivalent self fluxing material from Praxair is Ni-988, which contains 50% WC-12Co and 50% self-fluxing alloy, and appears to be a little more ductile.
5. Tribaloy 400, which is already being used on some IDs, as well as some actuator piston heads. This is a good material to use for applications where side loads may cause excessive piston head wear, since the material is not too hard, but is quite lubricious.
6. WC-CrC-Ni, which is a material developed by Praxair. This material was added to the matrix because it showed high hardness but was not a standard WC-Co. It does not appear to perform particularly well in wear and is not recommended.

The testing performed in this project showed that plasma spray carbides are effective ID chrome alternatives. Tribaloy coatings, which are used for some ID applications, are not as wear resistant as chrome, although they are relatively lubricious. The results can be summarized as follows:

**Adhesion** – The coatings have adequate adhesion (similar to the values normally found for plasma spray coatings), although, as expected, the adhesion strength is not as high as for HVOF coatings or for the metallurgically bonded hard chrome.

**Hardness** – The hardness of the WC composite coatings (Co and self-fluxing binder) are comparable with hard chrome. As expected, Tribaloy coatings are significantly softer.

**Abrasive wear** – Abrasive wear of the WC self fluxing composites is comparable with hard chrome, while WC-12Co wears at about half the rate of EHC. The softer Tribaloy coatings, of course, have a significantly higher abrasive wear rate.

**Sliding wear** – Sliding wear performance of the WC-Co and WC self-fluxing composites is similar to EHC. The coatings themselves wear a little more than EHC, but the total system wear is essentially the same. Wear of Tribaloy coatings is significantly higher than hard chrome.

**Corrosion** – In common with HVOF WC-Co coatings, corrosion tests using electrochemical

measurements show significantly higher corrosion currents for the plasma spray coatings. This is now expected since these methods measure the dissolution rate of the matrix material, whereas for EHC they measure dissolution of the substrate through cracks and porosity in the EHC. B117 salt fog tests were therefore also conducted to compare corrosion performance. These also showed high corrosion through the porosity in the coating. It was concluded that these coatings are not suitable for use in high corrosion environments, but are well suited for such applications as hydraulic actuators and dampers, which is where they are now being used in commercial aerospace units.

In addition to the coatings indicated above, Sulzer Metco evaluated many other materials but found none whose performance exceeded WC-12Co.

The limitations of the process are primarily the diameter and depth that can be coated. Depth is determined by the length of the extension that carries the gun. The standard lengths are generally 18-48", but longer extensions can usually be supplied by the manufacturer. If the extension is too long, however, the gun will not be able to be moved and operated stably. The minimum coatable diameter is defined by the size of the plasma gun plus the standoff (required gun-surface distance). For the guns primarily tested in this program, the Praxair 2700 and the Sulzer Metco F210, this diameter is about 2.75". For the larger and more cost-effective Sulzer Metco F100 it is 4". This limits plasma spray to landing gear and utility actuators, with most flight surface and engine actuators having too small a diameter. However, a new miniature ID gun, the F-300 from Sulzer Metco, has proved capable of producing apparently satisfactory coatings inside a 1.6" ID. This makes the method viable for coatings on components such as flight surface actuators, dampers and snubbers, as well as the landing gear and utility actuators accessible with larger guns. Even this gun, however, cannot be used inside small IDs such as LVDT (linear variable differential transformer) cavities in actuator rods. A new type of pulse thermal spray (detonation) gun has been developed at SAIC. This equipment appears capable of coating smaller IDs with high quality coatings, although it must be evaluated for comparison with the existing commercial equipment.

Since this work was completed a new ID HVOF torch has been developed by Northwest Mettech that appears be able to spray IDs as small as 90mm (about 4"). This will greatly improve the deposition rate and coating quality for ID thermal spray coatings.

A new Fumespector laser particulate monitor was developed by NRC to measure the density of overspray dust in the atmosphere within the ID. This was applied to measuring overspray removal using several different sparging gas arrangements, and led to Praxair's adoption of a dual gas jet arrangement for the 2700 gun.

The cost-effectiveness of the process was evaluated for ID coatings at NADEP Jacksonville using a full Implementation Assessment based on the C-MAT decision tool. This showed that process cost using the smaller guns would be almost twice the existing chrome plating cost, but that if the higher deposition rate F100 gun were used the costs of EHC and plasma spray would be approximately equivalent. However, a much-reduced OSHA PEL for $Cr^{6+}$ has now been proposed and is expected to greatly increase chrome plating costs for many operations. Using estimates from a Navy/Industry study it was estimated that DoD chrome plating costs will double. This will make plasma spray cost-competitive even when using the small guns, and cost-effective for larger ID guns such as the F100. However, the primary reason for instituting ID plasma spray at NADEP JAX is not cost but turnaround. Because it eliminates the need for hydrogen baking and can be done faster when using larger ID guns, it decreases time-in-process. All the depots are attempting to reduce turnaround so as to return equipment to the field as rapidly as possible to improve readiness and increase war fighting capacity. Plasma spray for IDs, like HVOF for ODs, is part of this effort.

# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# LIST OF ACRONYMS

| | |
|---|---|
| AE | acoustic emission |
| AFRL | Air Force Research Laboratory |
| ASTM | American Society for Testing and Materials |
| a.u. | arbitrary unit |
| CBA | cost/benefit analysis |
| C-MAT | Calculation for Materials Alternative Technologies |
| CVD | chemical vapor deposition |
| D | Diamalloy (when used in powder designation, e.g., D2002) |
| DOD | Department of Defense |
| EHC | electrolytic hard chrome |
| EIS | electrochemical impedance spectroscopy |
| ESD | electrospark deposition |
| ESOH | environment, safety and occupational health |
| GEAE | GE Aircraft Engines |
| HA | hydraulic actuator |
| HCAT | Hard Chrome Alternatives Team |
| HVOF | high-velocity oxygen-fuel |
| ID | internal diameter |
| IRR | internal rate-of-return |
| JSF | Joint Strike Fighter |
| LG | landing gear |
| lpm | liters-per-minute |
| LVDT | linear variable differential transformer |
| MLG | main landing gear |
| NADEP | Naval Air Depot |
| NADEP-JAX | Naval Air Depot Jacksonville |
| NLOS | non-line-of-sight |
| NPV | net present value |
| NRC-IMI | National Research Council (Canada) Industrial Materials Institute |
| NRL | Naval Research Laboratory |
| O&R | overhaul and repair |
| OD | outside diameter |
| OEM | original equipment manufacturer |
| OSHA | Occupational Safety and Health Administration |
| PEL | permissible exposure limit |
| psi | pounds per square inch |
| PVD | physical vapor deposition |
| QC | quality control |
| ROI | return-on-investment |
| SERDP | Strategic Environmental Research and Development Program |
| SF | self-fluxing |
| SM | Sulzer-Metco |
| TDC | thin dense chrome |
| TRL | Technology Readiness Level |
| T-400 | Tribaloy 400 |
| T-800 | Tribaloy 800 |
| UTS | ultimate tensile strength |

# Powder Cross Reference

It is common in the industry for sprayers to reference the powder designation rather than the coating chemistry, and this is done on some charts in this report. The following table cross references powder designations and chemistry.

| Powder | Manufacturer | Common name | Chemistry |
|---|---|---|---|
| Amdry 9830 | Sulzer Metco | | WC-17Co |
| **Co-109-3** | Praxair | Tribaloy 400 | Co-28 Mo-8 Cr-2 Si |
| Co-111 | Praxair | Tribaloy 800 | Co-24Mo-17Cr-3Si |
| **Diamalloy 2002** | Sulzer Metco | WC-Co self fluxing | 55%(WC 12Co) 45%(33Ni 9Cr 3.5Fe 2Si 2B 0.5C) |
| **Diamalloy 2003** | Sulzer Metco | WC-cobalt | WC-12Co |
| Diamalloy 2005, 2005NS | Sulzer Metco | | WC-17Co |
| Diamalloy 2006 | Sulzer Metco | | WC 17Co |
| Diamalloy 3007 | Sulzer Metco | | $Cr_3C_2$ 20(Ni 20Cr) |
| Diamalloy 4008 | Sulzer Metco | Nickel aluminide | Ni5Al |
| Metco 439NS-2 | Sulzer Metco | WC self fluxing | WC-12Co + Ni based self-fluxing alloy |
| **Ni-988** | Praxair | WC-Co self fluxing | 50%(WC 12Co) 50%(33Ni 9Cr 3.5Fe 2Si 2B 0.5C) |
| SM 5803 | Sulzer Metco | | (WC 12Co) 25(Ni-Based Superalloy) |
| SM 5810 | Sulzer Metco | | WC-12Co |
| SM 5826 | Sulzer Metco | | WC-17Co |
| SM 5843 | Sulzer Metco | WC-CoCr | WC 10Co 4Cr |
| SM 5847 | Sulzer Metco | | WC 10Co 4Cr |
| SM 5848 | Sulzer Metco | | WC 10Co 4Cr |
| **WC-496** | Praxair | WC-CrC-Ni | W 20Cr 6Ni 6C |

Bold items optimized in this program.

# ACKNOWLEDGMENTS

The financial and programmatic support of the U.S. Department of Defense, Strategic Environmental Research and Development Program (SERDP), under the direction of Mr. Bradley Smith, Executive Director, Dr. Jeffrey Marqusee, Technical Director, and Mr. Charles Pellerin, Program Manager for Weapons Systems and Platforms, is gratefully acknowledged.

The authors would also like to acknowledge the following individuals who made substantial contributions to the execution of the project:

Mr. Stephen Gaydos, Boeing Corporation, St. Louis, MO

Mr. Roger Eybel, Messier-Dowty, Toronto, Canada

Mr. Roque Panza-Giosa and Mr. Ben Evans, Goodrich Corporation, Toronto, Canada

# 1. Project Background

High-velocity oxygen-fuel (HVOF) thermal spray has become the method of choice to replace hard chrome plating on outside diameters (ODs) for commercial and military aircraft OEMs and most DOD aircraft depots. It is now used for landing gear pistons and axle journals, hydraulic rods, slat and flap tracks, engine shaft journals, and numerous other external surface, line-of-sight applications on wear components. However, HVOF is a line-of-sight spray technology that cannot be used for many non-line-of-sight (NLOS) geometries such as internal diameters (IDs). HVOF guns are quite large and require a standoff (distance from gun to surface) of several inches. They can only be used for ID coating if the ID can be reached from outside by angling the gun to a maximum of 60° off-normal [1] (Figure 1-1). An example of this is the qualified repair of a Canadian F-18 axle polygon (white area in Figure 1-2). IDs smaller than about 11" and with an aspect ratio greater than about 1.5:1 (length:diameter) cannot be HVOF-sprayed.

**Figure 1-1. ID coating by HVOF.**

**Figure 1-2 CF-18 A/B axle polygon HVOF sprayed from outside (Messier-Dowty).**

Consequently, there is a need for an ID coating technology that is clean, can be used for rebuilds, and is environmentally acceptable. To be accepted it is critical that it fit with both the OEM and the depot maintenance production environments, and that it cover the very broad range of thicknesses commonly found in ID coatings - about 0.001" - 0.015". Furthermore, as a practical matter a chrome replacement will be more readily accepted if it uses similar materials and technologies to those already in use or being validated for chrome replacement on external surfaces. Lower cost, better performance and faster turnaround time are additional drivers for change. For these reasons another thermal spray technology, plasma spray, is being developed for ID chrome replacement, and is already used for some limited ID applications.

## 1.1. Usage of ID and NLOS chrome

The following ID chrome plating examples are mostly taken from the report on ID alternatives written for the Joint Strike Fighter Program [2] and are included for illustration of the issues involved in ID chrome replacement of different types of components.

Manuscript approved July 11, 2006.

### 1.1.1. Blind and through holes in landing gear and hydraulic cylinders

Only on the largest aircraft are the landing gear (LG) cylinders large enough in diameter to accommodate a standard HVOF gun, which can coat inside holes only above about 11” ID. Outer cylinder IDs of both landing gear and actuators are often chrome plated for wear resistance (against seals) and for corrosion resistance against water contamination in the fluid. In many cases the coating material used is thin dense chrome (TDC) rather than standard chrome plate. Unlike standard chrome plate, TDC is a specialized and proprietary coating <0.001” thick, and there are very few vendors capable of doing it well. Depots do not deposit TDC as any rebuild requires thick chrome.

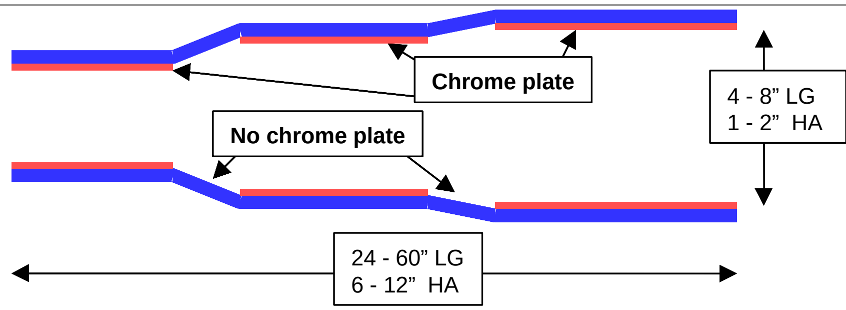



**Figure 1-3. Complex landing gear outer cylinder cross-section.**

Figure 1-3 shows a cross section that is quite common in landing gear outer cylinders (although many are simpler than this, with only a single ID). In this case the coating is used only on the working surfaces, and is specified as uncoated on transition areas. When chrome plating cylinders of this type, Heroux uses conformal anodes with insulators to shield the areas where coating is not required. This avoids the complications and waste streams involved in masking difficult areas within the ID. Any replacement coating must either work without shields or it must be able to be shielded easily. Alternatively (and with more difficulty for existing parts) it may be possible to specify that the coating be permitted on the non-working surfaces.

Most of these items are basically cylindrical, although hydraulic actuators (HA) are often set into a block that contains many different actuators and other hydraulic components. Landing gear typically are several feet long and have large IDs, whereas hydraulics are typically no more than 12 inches long with an inch or so ID. Landing gear outer cylinders are usually made of 300M (or, for the Navy, AerMet 100) high strength steel or 7075 aluminum alloys. Hydraulic actuator outer cylinders are typically 7075 aluminum or 4340 high strength steel.

### 1.1.2. Specific components

Internal chrome plating is most prevalent on landing gear components and hydraulic actuators. A number of different types of these components have been identified by Messier-Dowty and Boeing as posing various problems for standard HVOF coating, either because they require ID coating or because access to the area to be coated is difficult. This is by no means an exhaustive catalog of components, but is meant to illustrate the major categories of problems that might be encountered.

#### 1.1.2.1. Landing gear cylinders

Figure 1-4 shows the ID of a P-3 main landing gear. This single item represents a large part of the ID plating area workload at NADEP Jacksonville. ID plasma spray of this size item would be fairly simple because of its 8.5” diameter, although its 4-foot length would necessitate a longer

than standard gun extension since access is only through the open end (shown).

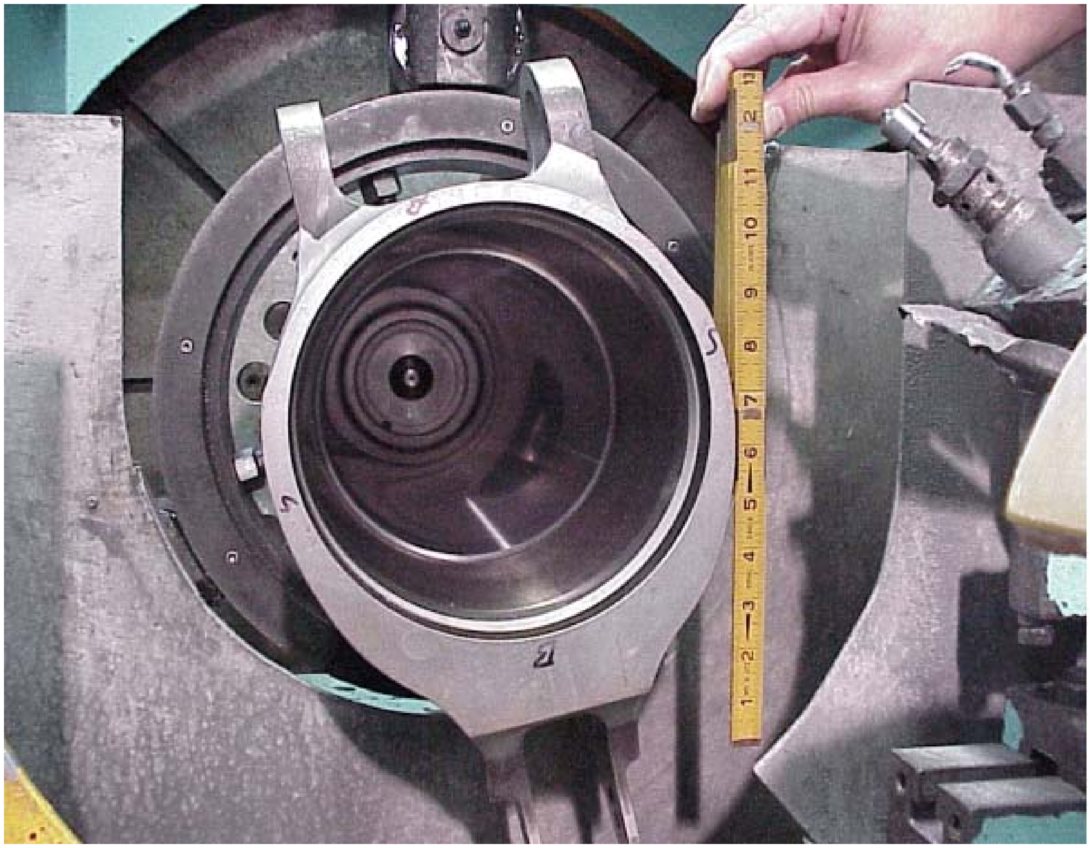


**Figure 1-4 P-3 main landing gear outer cylinder ID chrome plated at NADEP JAX.**

On the other hand, a typical fighter main landing gear outer cylinder is shown in Figure 1-5. This 4.9” ID item has only one open end and must be coated over a depth of about 2 feet. Note also that the coating is specified to break at the internal ID step, which is quite common with this type of item and requires proper masking. This size component cannot be HVOF sprayed. However, with a diameter of almost 5” and openings at both ends, this item can readily be plasma sprayed.

One of the largest military landing gear outer cylinders is for the C-17 (Figure 1-6). In this case, not only is the ID large, but the chrome is required close to the open end, making it fairly easy to HVOF spray at an angle from the open end. The spray angle is 50° to the axis, making a high quality HVOF coating possible.

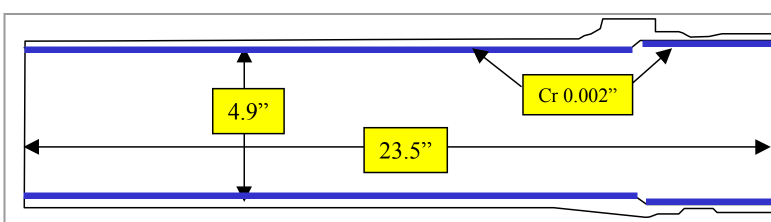



**Figure 1-5. F-15E MLG outer cylinder bore, 300M steel. Manufactured by Goodrich Aerospace. Courtesy Boeing.**


**Figure 1-6 Boeing C-17 and section of nose landing gear cylinder, 300M steel. Manufactured by Goodrich Aerospace. Courtesy Boeing.**

### 1.1.2.2. Actuators

Figure 1-7 shows a rather typical flight surface actuator - the aileron actuator from an F-18. The 2.5” ID bore has a total depth of about 7” and is accessible only from one end. The chrome is resin sealed for corrosion resistance.

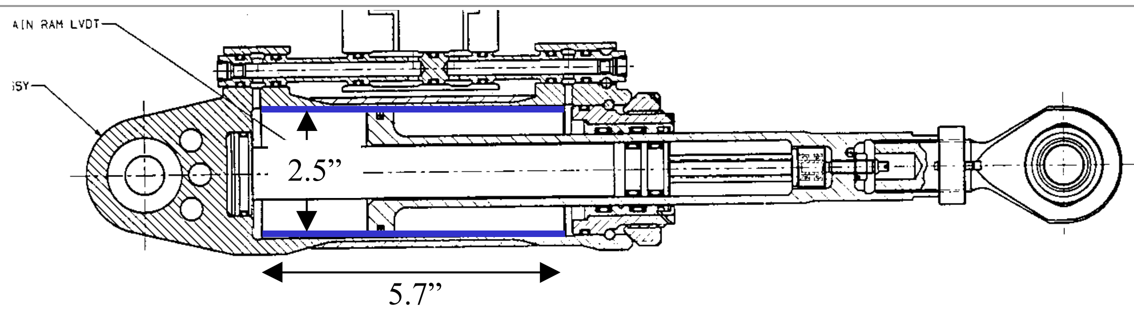



**Figure 1-7. F/A-18 E/F aileron servocylinder, manufactured by HR Textron - Courtesy Boeing.**

Actuators of this size are the smallest that can be coated with most existing plasma spray guns, although in this program we have tested a gun capable of coating well below this diameter. Flight surface actuators are frequently smaller in diameter than that of Figure 1-7 - with some smaller actuators having IDs of about 1”.

Landing gear and landing gear actuators built by Messier-Dowty frequently call out standard hard chrome (0.005” thick plate) on the OD and thin dense chrome (0.0005 - 0.0008” thick) on the ID.

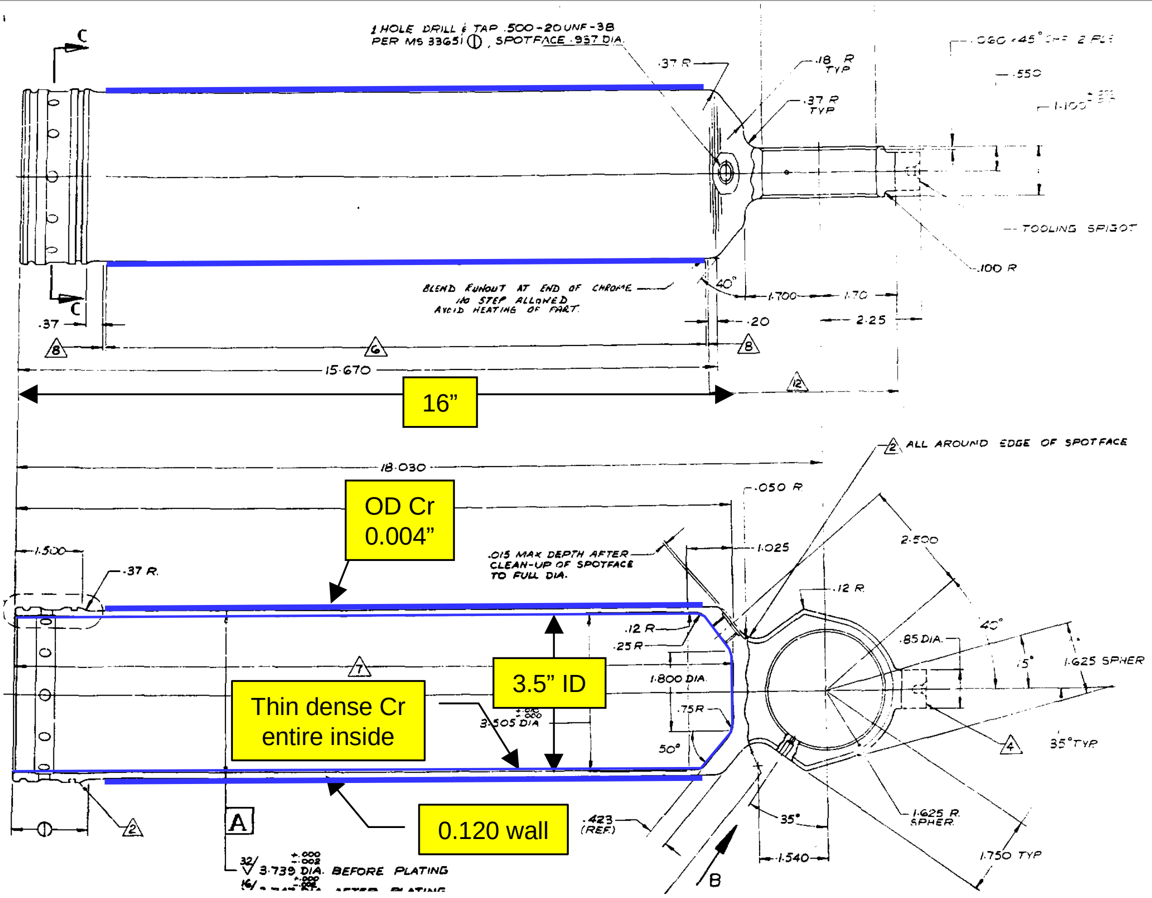



**Figure 1-8. Landing gear actuator inner cylinder, (300M high strength steel). Courtesy Messier-Dowty.**

The inner cylinder of a high strength steel actuator of this type is shown in Figure 1-8. The OD chrome plate can be readily replaced by HVOF coatings. Its purpose is to provide a wear resistant surface to bear against the guide bushing and to prevent wear of the outer cylinder seals. The thin dense chrome on the inside is for a combination of corrosion resistance and wear resistance against internal seals.

The ID chrome cannot be replaced by HVOF WC-Co using current HVOF equipment. It could be replaced by plasma sprayed WC-Co, since the ID will accommodate a standard plasma spray ID gun. However, in order to make the internal coating a drop-in replacement, the coating would have to be less than 0.001” thick, with low enough porosity to prevent corrosion or leak-by, and the gun would need to coat both the walls and the end. Since the wall thickness is only 0.12”, heat from the gun would have to be dissipated effectively, which could presumably be done by cooling both the inside and the outside of the cylinder. This type of component would be overhauled by thick chrome plating, which could be replaced by plasma spray, but could not be OEM-coated this way without changing the thickness specification and machined size.

A larger landing gear actuator inner cylinder is shown in Figure 1-9. It is very similar to that of Figure 1-8, but is about twice the size. Any method used to coat this item internally would require a reach of about 6 feet, and would need to coat approximately 1,100 square inches uniformly and cost-effectively. Again, the OD chrome is readily replaced by HVOF WC-Co.

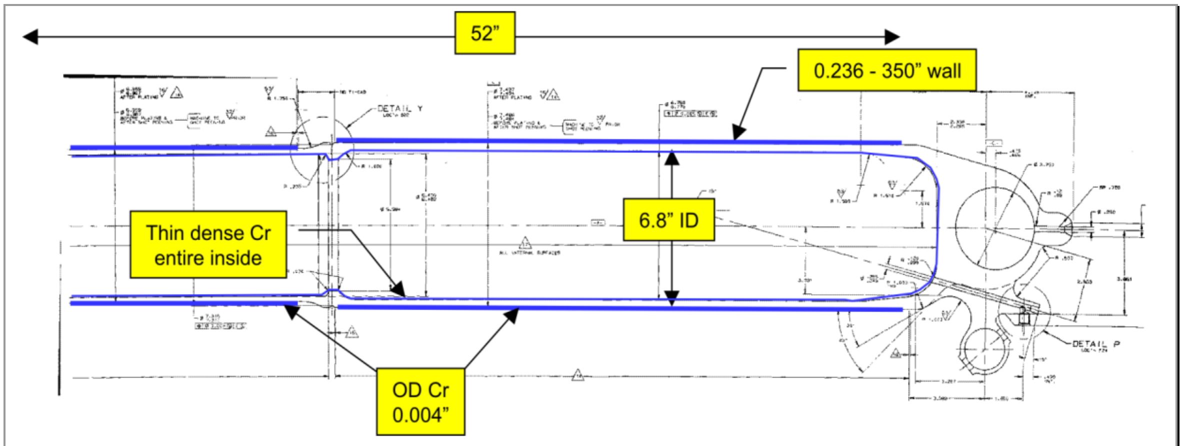



**Figure 1-9 Landing gear actuator inner cylinder - courtesy Messier-Dowty (300M steel).**

It should be noted that in both of these actuators the ID is a blind hole. As indicated below, ID plasma spray is more difficult in blind holes since overspray (powder that is not melted and bounces back off the part) must be rapidly swept out of the area to avoid entrainment in the coating. This is fairly easy to do with open-ended tubes, but more difficult with blind holes.

#### 1.1.2.3. Landing Gear Pins

In contrast to these large items, landing gear pins are some of the smallest landing gear components that are frequently chrome plated. In most cases pins are chromed only on the outside to resist wear and galling. In some cases, however, the IDs of pins must be coated to protect them from wear against locking devices and end caps, and to provide additional corrosion protection. Figure 1-10 shows such an internally chromed pin.

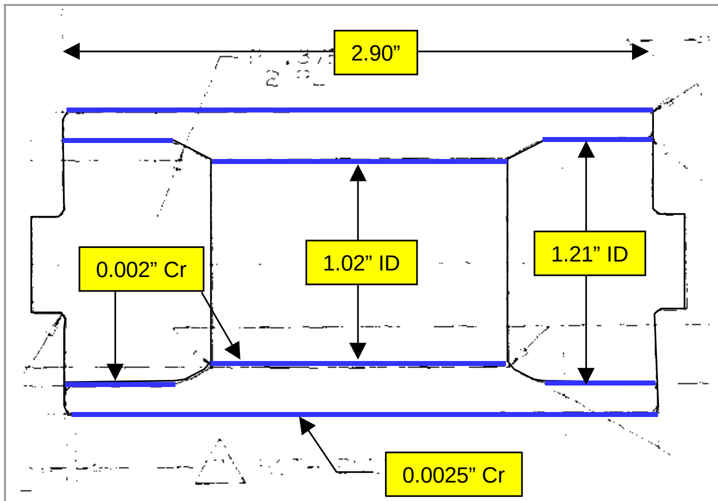



**Figure 1-10. 300M pin for MLG shock strut piston - courtesy Messier-Dowty.**

The 1.21" diameter recesses on the ends of such a pin could be readily coated by an HVOF gun angled into the ID. The 1.02" ID is more difficult to HVOF spray. However, the area could be reached with a torch angled at 30° to the axis of the pin, which has been shown to produce coatings of acceptable quality [1]. Therefore this component could be HVOF coated both inside and out, and ID plasma spray would not be a viable option as the ID is too small.

In contrast to the pin shown in Figure 1-10, the F/A-18 nose landing gear torque arm pin shown in Figure 1-11 is the same diameter, but longer, and is unlikely to be ID coated reliably with current HVOF equipment, since the spray angle required to reach the center would be about 20° to the axis. GEAE reports that in some cases HVOF spray can be done at this angle, but the reliability of such a coating within the narrow confines of this component would be suspect.

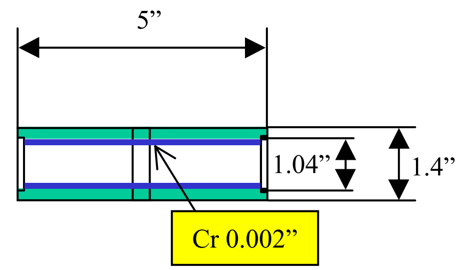



**Figure 1-11. F/A-18 E/F NLG torque arm pin, Aermet 100. Manufactured by Messier-Dowty. Courtesy Boeing.**

### 1.1.3. Summary of component coating requirements

The primary requirements for ID chrome replacement are summarized in Table 1-1. The fact that standard HVOF guns can only be used for components above 11” ID restricts them to only the largest landing gear, or to shallow IDs whose depth is no greater than about one diameter, which can be sprayed at an angle from outside. (A new HVOF ID is now commercially available that can spray down to 4” ID, but this was not available during the course of this work.) Plasma spray could be used for almost all landing gear outer cylinder IDs, but is currently too porous as-sprayed. Prior to this program it was felt that this problem might well be solvable by the use of small- or nano-particle spray methods (which should also permit coatings to be thinner), although of course, a polymer sealant could also be used, just as it is with chrome plating when used in this type of application.

**Table 1-1. Hard chrome replacement criteria (from Ref 2).**

| Issue | Criteria | Notes |
|---|---|---|
| **ID coating requirements** | | |
| Hole dimensions | Actuators: 1" min. dia. by up to 24" long<br>Landing gear, large actuators: 3-15" dia by up to 60" long | |
| Hole geometry | Open, blind, some internal grooves | |
| Coating thickness | OEM: 0.003"<br>OEM thin dense Cr: 0.0003"<br>O&R: 0.003-0.015" | |
| Smoothness | 16µ" Ra typical, some replacements may need to be 4µ" Ra | Highly useful to be able to deposit thin coatings to replace thin dense Cr, without need for grinding. (As-deposited Ra<8 µ".) |
| Deposition temperature | High strength steels: <250°C<br>Aluminum alloys: <150°C | Critical issue is time-at-temperature. Critical issue is fatigue reduction due to changed surface microstructure. |
| **Technical issues** | | |
| Wear resistance and hardness | Match performance of chrome on actual components | Critical issue is wear life (wear rate x thickness) in service, and avoidance of seal wear in hydraulics |
| Corrosion resistance | Must match chrome - primarily B117 salt fog | Microcracks make chrome a poor corrosion inhibitor - may require sealer or Ni underlay. |
| Hydrogen embrittlement | None | This is a critical flight safety issue |
| Fatigue | Fatigue debit must not exceed chrome | Navy particularly concerned with NaCl and $SO_2$ atmospheres - critical flight safety issue. |
| **Producibility** | | |
| Reproducibility | Process must be stable | Both OEM and O&R environments |
| Process window | Within day-to-day operating parameters | Simple, reasonable QC needed |
| Cost | Total production cost comparable to 2 x chrome.<br>Life-cycle cost < chrome<br>Reasonable capital cost | Production cost needs to include cleaning, masking, finishing, heat treating, waste disposal, etc. |
| **OEM and O&R fit** | | |
| Stripping | Must be able to be stripped - safe chemicals, water jet, etc | Strippability is <u>crucial</u> to O&R. |
| Field and O&R chemical stability | Must withstand O&R cleaning, chemicals, hydraulic fluid, etc. | Must not deteriorate when put through O&R process |
| Environment/safety | Must be environmentally benign and safe for workers | Note that O&R operations are more diverse and less easily controlled |
| **Acceptance issues** | | |
| Specifications | AMS and/or aircraft company specifications needed | Cannot be specified and put on drawings without specs. |
| Proprietary technology | Cannot be proprietary to one company | If possible, should be able to be done at general O&R site to avoid sending out |

## 1.2. ID chrome alternative technologies

There are a number of viable options to replace ID chrome, summarized in a 1999 report to the JSF ESOH Working Group [2]. The summary of options from that 1999 report is given in Table 1-2. (At that point in time the nCo-P pulse plating had not yet been developed, which is why it was not included as an option.)

In 1999 SERDP funded three ID chrome alternative programs:

- PP-1152 Electroformed Nanocrystalline Coatings: An Advanced Alternative to Hard Chrome Electroplating (Babcock and Wilcox, Integran). This program developed a nanophase Co-P electroplate using pulse electroplating.
- PP-1151 Clean Dry-Coating Technology for ID Chrome Replacement (HCAT). This program evaluated plasma spray for internals.
- PP-1147 Electro-Spark Deposited Coatings for Replacement of Chrome Electroplating (Pacific Northwest National Labs). This program developed Electrospark Deposition, a microwelding technology.

In addition, AFRL has a long-running project to evaluate electro- and electroless plating for non-line-of-sight (NLOS) chrome replacement [3], which has concentrated on Ni and Ni composites.

**Table 1-2. Summary of ID chrome replacement options for the Joint Strike Fighter (from Ref 2). Note: Since the date of the referenced report nanophase Co-P and ID HVOF guns have become available.**

| Technology | Principle | Company | Capabilities/Notes | Status OD | Status ID |
|---|---|---|---|---|---|
| **Thermal spray** | | | | | |
| HVOF | Powder + high temperature flame | e.g. Sulzer Metco, Praxair, TAFA, Northwest Mettech | 11" ID, WC-Co, alloys with standard guns. | Production | Used for shallow IDs coated from outside. |
| Plasma spray | Powder + plasma | e.g. Sulzer Metco, Praxair | 1.5" ID, WC-Co, alloys, metals | Production | Production/short |
| Small/ nanoparticle thermal spray | Small particles + plasma or flame | SUNYSB, ONR, U. Conn, NU. ONR (Larry Kabacoff), DARPA funding | Dense coatings, WC-Co, oxides. May make smaller guns possible | Research | Research/inter |
| **Weld coating** | | | | | |
| Electrospark (ESD) | Microarc weld | Advanced Surfaces and Processes, Batelle PNL | <0.5" ID, 120" long nanophase WC-Co, alloys. Smal diameter only | Development | Development/short |
| Explosive clad | Explosive bonding | Sigmabond Technologies | Metals, WC-Co | Research | |
| **PVD/CVD** | | | | | |
| Post-magnetron | Sputtering from high current rod | Surface Solutions, Praxair (ATP program), Army Benet Labs | Metals, alloys, nitrides; Ta (Army) | Development, research | Development/inter |
| CVD, MOCVD, plasma CVD | Deposition from gas | Various | Very small, long holes. High temperature/dangerous precursors | Production | |
| Combustion CVD | Precursors combined in flame | MicroCoating Corp | Compounds (oxides, etc). VOC solvents used | Research Development | Research/long |
| Plasma CVD | Precursors deposited by plasma | Metroline | Oxides, nitrides, metals | Production | Research/long |
| Hollow cathode evaporation | Small internal hollow cathode | U. Uppsala (Sweden) | Metals, nitrides. Low build-up | Research | |
| Laser deposition | Laser evaporation, alloying, and CVD | QQC Diamond | Diamond. No build-up | Research | |
| Laser Induced Surf. Improvement (LISI) | Laser alloying | Surface Treatment Technology, University of Tennessee | Alloys with surface material (not coating). No build-up | Research | |
| Plasma nitride | Nitriding at about 500C | e.g. Advanced Heat Treat | Surface treatment (no build-up, high temperature) | Production | |
| **Wet plating** | | | | | |
| Electroless Ni and Ni composites | Electroless Ni-P/B (+ SiC, Teflon, diamond, etc), Amplate | Various | Ni-P, Ni-B, and particle-filled alloys | Production | Production/iimmed |
| Brush plating | Ni electroplate | Various | Cr, Ni, other metals | Production | |
| Alloy plating | Electroplating of simple alloys | Various | Ni-W-B, Co-W | Production | Production/short |
| Co-composites, Tribomet® | Co alloy composite plate | Praxair | Co alloy, proprietary | Production | Production/short |
| | | | | | |
| Immediate | Short term | Intermediate term | Long term possibilities | Not applicable to JSF IDs | |

# 1.3. ID plasma spray project

## 1.3.1. Objective

With plasma spray, the basic materials are known to be acceptable for most applications but, with a porosity often close to 10% they are too porous as-sprayed for most landing gear and hydraulic cylinders. However, they could be sealed as is typically done with chrome plate. (Boeing usually specifies a vacuum impregnation sealer for ID chrome plate to seal against permeation through its crack pattern.) The critical issues for plasma spray ID coatings are:

1. Plasma spray coatings must have low enough porosity (or be adequately sealed) for use in hydraulic actuators and landing gear outer cylinder IDs. Porosity requirements for hydraulics require that there be no fluid leakage around the seal through the coating in systems operating at up to 5,000 psi. Unlike hydraulic actuators, landing gear are gas-over-fluid systems in which it is essential to prevent gas leakage around the seal through the ID coating.
2. It must be possible to coat cost-effectively over a large enough range of thickness to replace the majority of ID chrome, from thin 0.001" coatings to high rebuild chrome (>0.010"). (Note: thermal spray is not a viable replacement for thin dense chrome.)
3. The portion of the market that ID plasma spray can address depends on the size and reach of ID plasma spray guns. For use in landing gear, plasma spray guns must be able to coat 4" ID and above. For utility actuator IDs they must be able to coat 2-4" IDs to depths of several feet. For use in flight surface actuators they must be small enough to produce reliable coatings in IDs less than 3".

The objectives of this program were:

- To develop methods for creating smooth, low porosity plasma spray WC-Co coatings suitable for actuators and high pressure gas-over-fluid landing gear components >2.5" ID, using existing commercial guns with commercially available powders, of different sizes and/or with agglomerated nanoparticles.
- To develop and test a new miniature ID plasma spray gun for use with standard powders, small particles and nano-agglomerates. This new gun is designed to spray items with IDs down to 1.5" using standard spray particles.
- To evaluate the properties and performance of ID plasma spray coatings, and their fit with OEM and DoD operations.
- To evaluate costs compared with ID chrome plating.

The project was designed to improve the underlying science of plasma spray coatings, to demonstrate proof-of-principle for the plasma spray method, and to feed directly into an equipment and process development and validation work expected to follow rapidly upon the completion of the SERDP program. The project was aimed specifically at aircraft and hydraulics, since aircraft are used by all the services and constitute some of the most critical and difficult chrome replacement problems, while hydraulics are ubiquitous in all land-, air- and sea-based military systems. Materials and methods developed for the OEM and sustainment communities would therefore be equally valid for aircraft, vehicle, and shipboard use.

There are three ID chrome plating applications that the program was <u>not</u> designed to address:

1. Gun barrels, since gun barrel erosion and wear mechanisms are entirely different from those experienced by hydraulics and other similar items.

2. Thin dense chrome (TDC), which is 0.0001-0.0006" thick and is often used by OEMs as a wear coating in landing gear and hydraulic cylinder IDs. TDC is frequently unreliable and is not used by depots since TDC processes are specialized and proprietary. In any case, damage to such a coating usually requires stripping, remachining, and then replating with standard thick chrome to bring the part back to specification.
3. Linear variable differential transformer ( LVDT ) position sensor holes in hydraulic rods. These are often chrome or TDC plated, but cannot be thermal sprayed since they are deep and typically about half an inch in diameter.

### 1.3.2. Approach

The technical approach for this program is summarized as follows:

**Task 1.1. Standard ID gun**: Develop the plasma spraying of standard and small powders using commercially available internal diameter plasma guns (ID's > 3 inches) and miniature ID guns. Powders and coatings investigated included WC/Co, WC-self fluxing alloy, and Tribaloy 400. Work included measurement of particle velocities and temperatures in-flight from the gun to the substrate as a function of powder size and agglomeration in order to readily transfer optimal coating conditions from one location to another. Coatings were sprayed onto test coupons and internal diameters.

**Task 1.2. Miniature ID gun**: Evaluate, characterize, and develop plasma spray guns for deposition of coatings onto small internal diameters of less than 3 inches, making limited design modifications of the miniature plasma spray guns if necessary. Control of overspray and temperature must be developed to maintain coating quality and prevent overheating of the substrate.

**Task 2.1. Materials evaluation**: Measure selected properties on the coatings deposited in Task 1 and correlate with the deposition parameters. For the coatings deposited both by the standard and the miniature ID gun the following properties were determined:

- porosity using metallographic techniques
- the phases present in the coating using X-ray diffraction
- microstructure using optical and electron microscopy
- microhardness
- the internal stress and strain-to-failure using Almen strips
- adhesion using tensile bond testing.

**Task 2.2. Coating performance**: Measure fatigue, wear, corrosion. Hydraulic performance was to be measured if a suitable test system could be found.

**Task 3.1. Technology evaluation**: Periodic meetings with a technology evaluation team were used to identify the types of components onto which the plasma spray coatings would be both required and amenable. Results of the studies on gun performance and the properties measurements were evaluated and put into context with OEM and depot requirements. Periodic meetings were also held with the other SERDP-funded teams developing ID alternatives – electrospark deposition (ESD) and nanophase Co alloy electroplate.

### 1.3.3. Team and structure

The team was structured as shown on Figure 1-12.

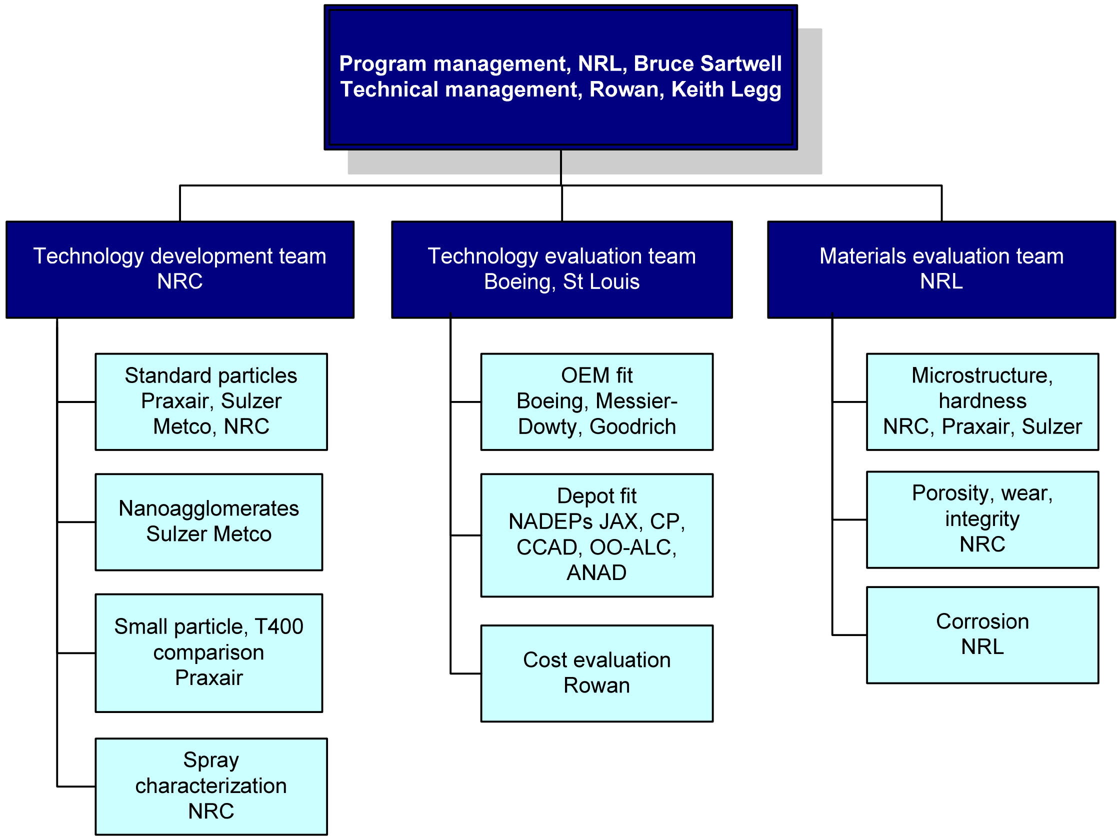



**Figure 1-12. Team structure.**

**The Technology Development Team** was led by Jean-Gabriel Legoux of the National Research Council of Canada's Industrial Materials Institute in Montreal. While the two primary manufacturers of thermal spray equipment, Sulzer Metco and Praxair, developed the coatings using their ID spraying equipment, NRC measured the particle temperature and velocity profiles so that the spray conditions could be transferred from site to site.

**The Materials Evaluation Team** was led by Bruce Sartwell at NRL to evaluate the properties and performance of the coatings. The coating structure and simple properties (hardness, Taber abrasion) were checked by Sulzer and Praxair as part of the development effort. Once the coatings were developed NRC tested their properties and performance (Section 4), except the corrosion testing, which was done at NRL.

**The Technology Evaluation Team** was led by Stephen Gaydos of Boeing, St. Louis, and included representatives of several depots and OEMs. The purpose of this team was to keep the program on track to meet the needs of the end users. The team met periodically (at HCAT meetings) and evaluated the program to determine whether it was answering their needs. In addition they provided feedback on the properties required of the coatings.

In addition, the program was coordinated with the other two SERDP programs evaluating ID chrome replacement with ESD coatings and nanophase electroplates (see Section 1.2) in order to evaluate the relative merits of the different ID coating approaches. These teams remained in contact throughout the program, with periodic meetings at HCAT Program Reviews, where each

of the teams also briefed their progress to the overall community. Data and briefings can be found on the HCAT web site at www.hcat.org and HCAT data sharing web site at www.materialoptions.com .

# 2. ID Gun Design and Characterization

Several guns were tested as part of this program:

1. Praxair 2700 gun
2. Sulzer Metco F210 gun, which is essentially equivalent to the Praxair 2700
3. Sulzer Metco F100 gun, which is larger and has a higher spray rate
4. Sulzer Metco F300 gun, which is a new, small ID gun that was not tested in this program except to determine its minimum spray diameter with self fluxing carbide powder (D2002).

Most of the work was done with the Praxair 2700 and the SM F210, with some testing using the F100 and F300 guns. Table 2-1 shows the capabilities of these guns.

**Table 2-1. Capabilities of ID guns.**

| ID gun | Minimum ID | Spray rate | Standard length | Notes |
|---|---|---|---|---|
| SM F100 | 4” | 2.4 kg/hr | 5.5”, 11”, 22” | |
| Praxair 2700 | 2.75” | 1.2 kg/hr | 12”, 24”, 36”, 48” | 45° and 90° nozzles |
| SM F210 | 2.75” | 1.2 kg/hr | 18”, 26” | 30° and 90° nozzles |
| SM F300* | 1.6” | 1.2 kg/hr | 9.8”, 17.7” | |

* Tested only superficially in this program.

Note: All guns can typically be supplied with custom extensions to reach different depths.

## 2.1. Gun design

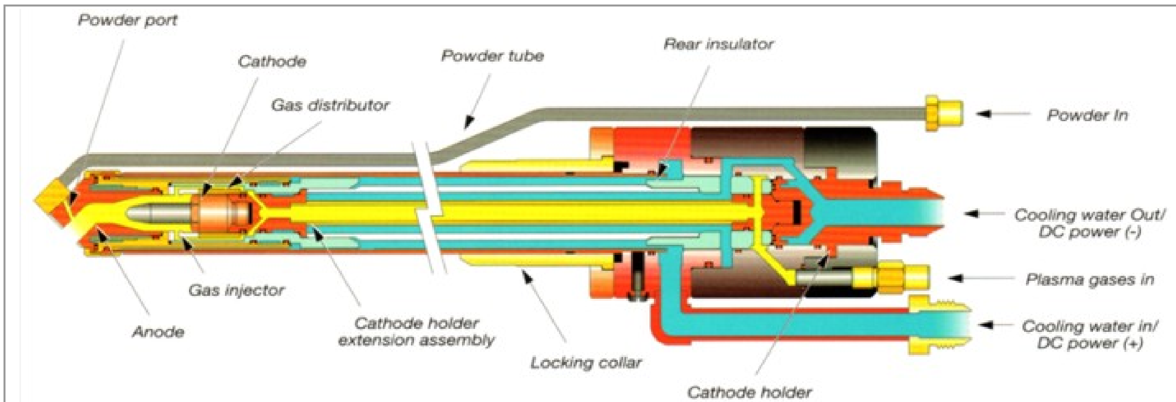



**Figure 2-1 Design of a typical ID plasma spray gun (Praxair 2086). (This design is very similar to the Praxair 2700 gun, which superseded it and was tested in this program.)**

The basic design of an ID plasma spray gun is shown in Figure 2-1. (This model was superseded by the 2700 gun, whose design is very similar.) Gas is fed into the gun while a potential between the cathode and anode creates a plasma. Powder is injected either within the gun (as shown) or by a tube immediately outside the exit orifice. The powder is heated by the plasma and softens,

while at the same time it is accelerated by the gas stream and lands on the substrate to form a coating. The spray direction is determined by the nozzle configuration and may be straight-ahead, 90° (normal to the wall of the ID), 60° or 45° depending on the gun design.

The two miniature guns are shown in Figure 2-2 in front of the 3" ID sample holder (described in Section 4.1). The designs are somewhat different but each is physically capable of being inserted into a 1.5" hole.

All guns use Ar for the primary (plasma) gas, He for the secondary plasma gas, and in some cases $H_2$ to modify performance.

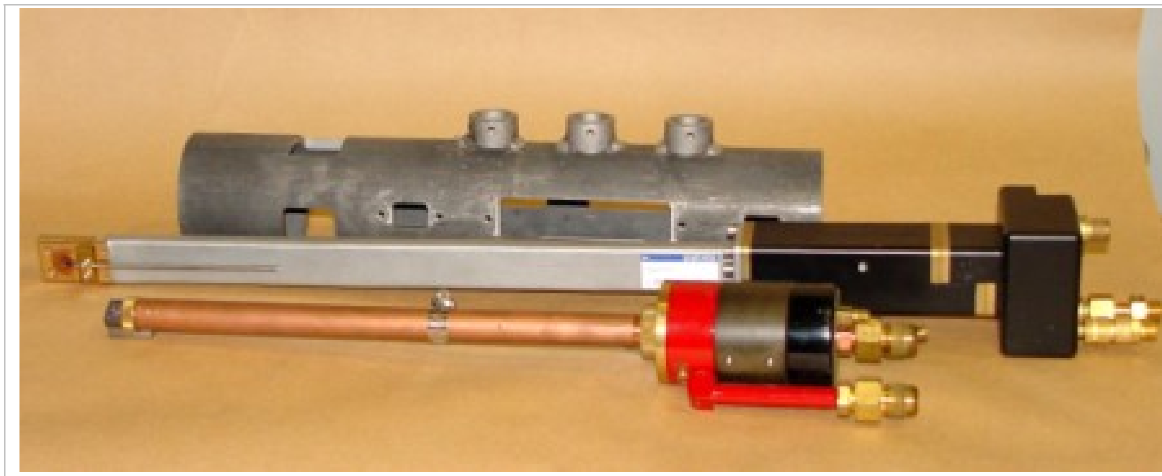


**Figure 2-2 Praxair SG-2700 gun (front) and Sulzer Metco F-210 gun (center) in front of the 3" ID, 18" long sample holder (back).**

## 2.2. Gun characterization

The plasma spray process depends upon a large number of parameters. However, once the powder leaves the gun the only factors that affect coating quality are

- Powder characteristics – particle size, shape, chemistry and morphology
- Particle velocity
- Particle temperature
- Substrate surface preparation (morphology) and temperature.

The powder characteristics are determined by the manufacturer and the method of manufacture, so the correct powder must be chosen. In order to transfer coating parameters from one piece of equipment to another at different locations it is only necessary to ensure that the particle velocity and temperature are the same. Therefore, to permit the parameters to be transferred, NRC characterized the temperature/velocity profiles produced by the different guns. This profiling was done using a DPV 2000 particle analyzer developed by NRC and sold commercially by Tecnar Automation of Canada, a spin-off from NRC-IMI. This instrument uses infrared emission from the flying particles to measure their temperatures and velocities. Once a coating is optimized in one location or with one gun the temperature/velocity data can be used to transfer it to another.

Initial profiling was done using the most common powders, such as Diamalloy 2005 WC-17Co, since final powder choices had not been made.

## 2.3. Sulzer Metco F-100 gun

The SM-F100 ID gun is shown in Figure 2-3. It is designed for diameters 4” and above and has a higher spray rate than the SM-F210 or Praxair 2700 guns.

**Figure 2-3 Sulzer Metco F100 ID gun.**

The operational ranges of the gun for different powders are shown in Figure 2-4 (2.5” standoff) and Figure 2-5 (1.25” standoff). The range of deposition conditions in these figures was

Gun power = 9-20 kW

Ar flow rate = 45-85 $lm^{-1}$

$H_2$ flow rate = 0.3-2 $lm^{-1}$ (when used)

He flow rate = 10-20 $lm^{-1}$ (when used)

Standoff = 1.25”-1.5”

F100 operational range.xls

Click on the yellow box above to view deposition details.

Temperature and velocity are higher when the standoff is lower (i.e. the gun is closer to the surface). This is easily understood from the profile of particle temperature and velocity along the axis of the gun, shown in Figure 2-6, which shows the particles slowing down and cooling as they travel away from the gun and hence the plasma that heats them.

The effect of gas flow rate on temperature and velocity is shown in Figure 2-6 and Figure 2-7. Note how temperature falls, but velocity rises with rising gas flow, as is expected. The effect of this on coating porosity (a critical property for coatings for actuators and landing gear) is shown in Figure 2-9. Clearly, one would like to operate at low flow rate for the best porosity. What this means is that, for the lowest porosity, the particles should be relatively hot and not too fast. This ensures that proper splat formation and flow of the splat material as individual thermal spray particles impact the surface. This in turn minimizes the splashing that can create voids and pores.

Flow rates and standoff must be properly balanced to obtain the best coating, but this can be difficult to do when the space is constricted, as in an ID. Figure 2-8 shows a method for raising the temperature and velocity by adding a small amount of hydrogen gas, which has a higher enthalpy, and provides additional control for particle temperatures and velocities. The effect of this is shown by the open- and closed-circle curves in Figure 2-6. Independent control of particle temperature and velocity is also illustrated in Figure 2-4, which shows the effect of depositing D2005 using argon and helium as well as with argon and hydrogen. Note how the use of hydrogen permits a higher particle velocity for the same temperature.

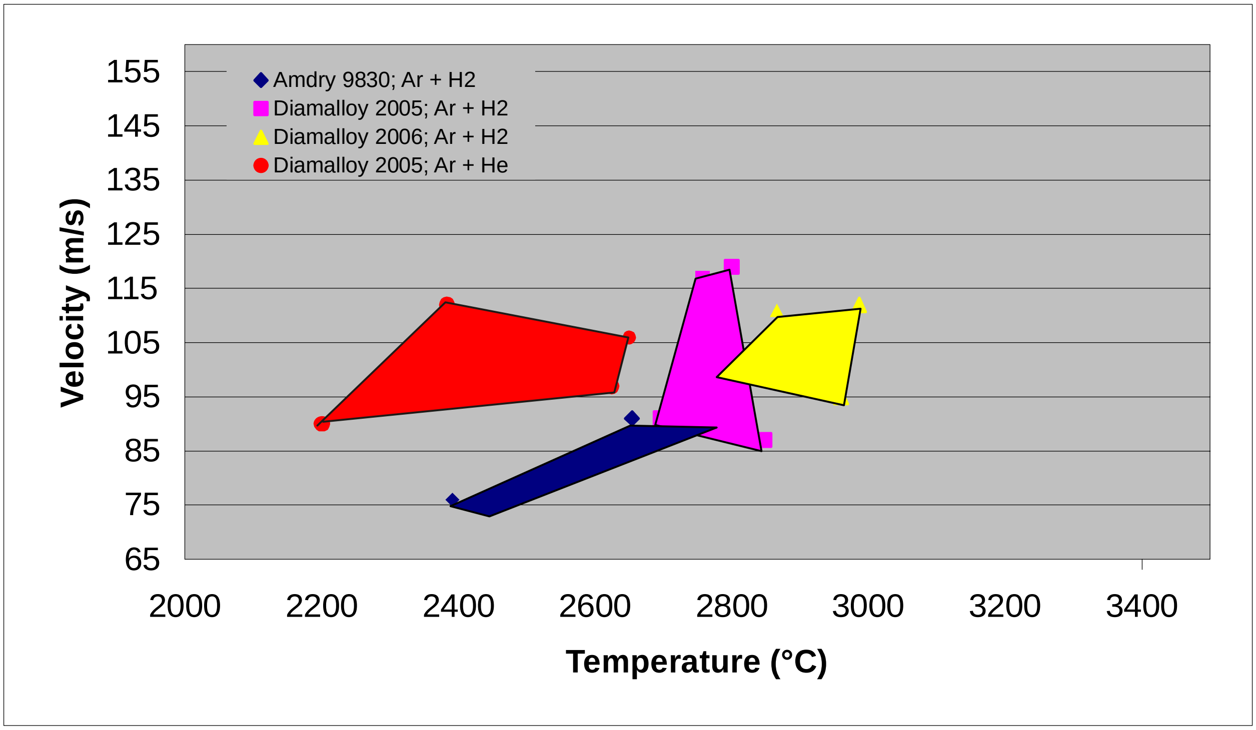



**Figure 2-4. Operational range for the F100 gun with WC-Co powders – 2.5" standoff. Note: Diamalloy 2005 run with He.**

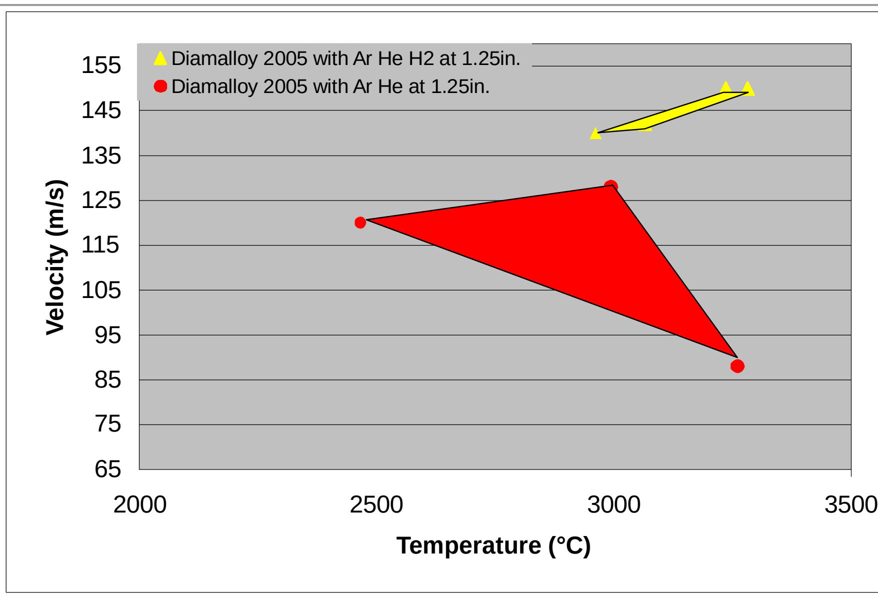



**Figure 2-5. Operational range for the F100 gun with Diamalloy 2005 WC-Co powders – 1.25" standoff.**

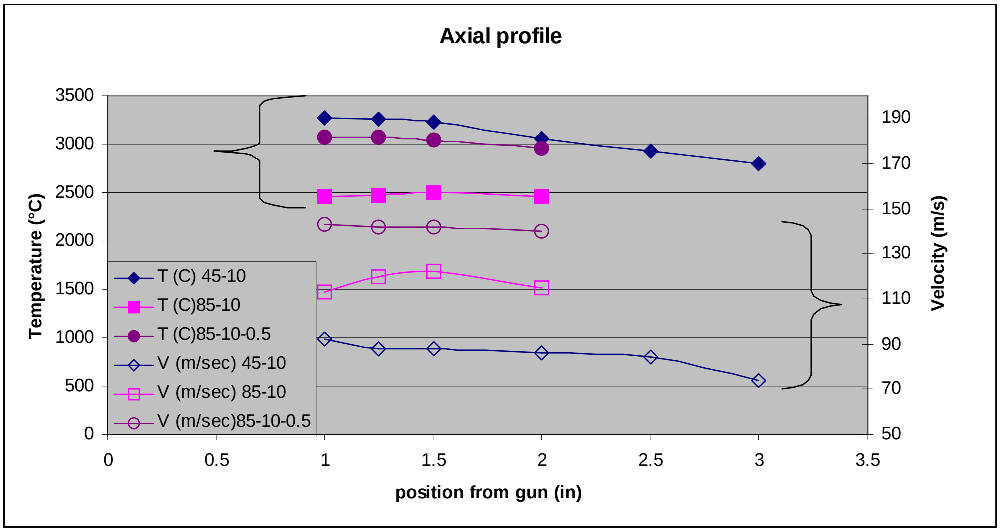



**Figure 2-6. Axial profile of particle temperature and velocity for the F-100 gun – Diamalloy 2005 WC-17Co powder, various gas flows. The numbers in the legend are gas flow (liters/min) for Ar, He, and (where used) $H_2$ respectively.**

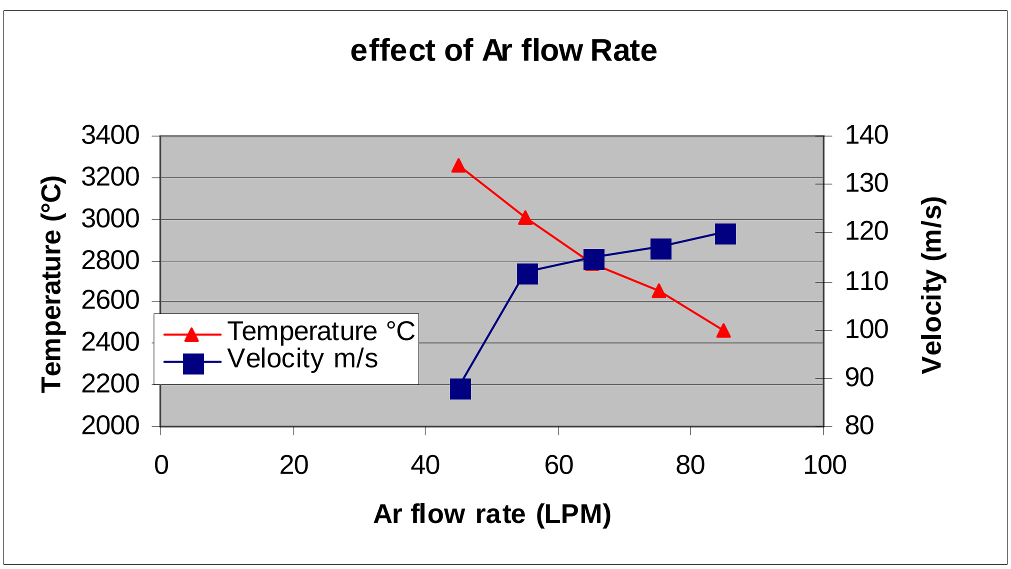



**Figure 2-7. Effect of Ar flow rate on particle temperature and velocity - F-100 gun, Diamalloy 2005 WC-17Co.**

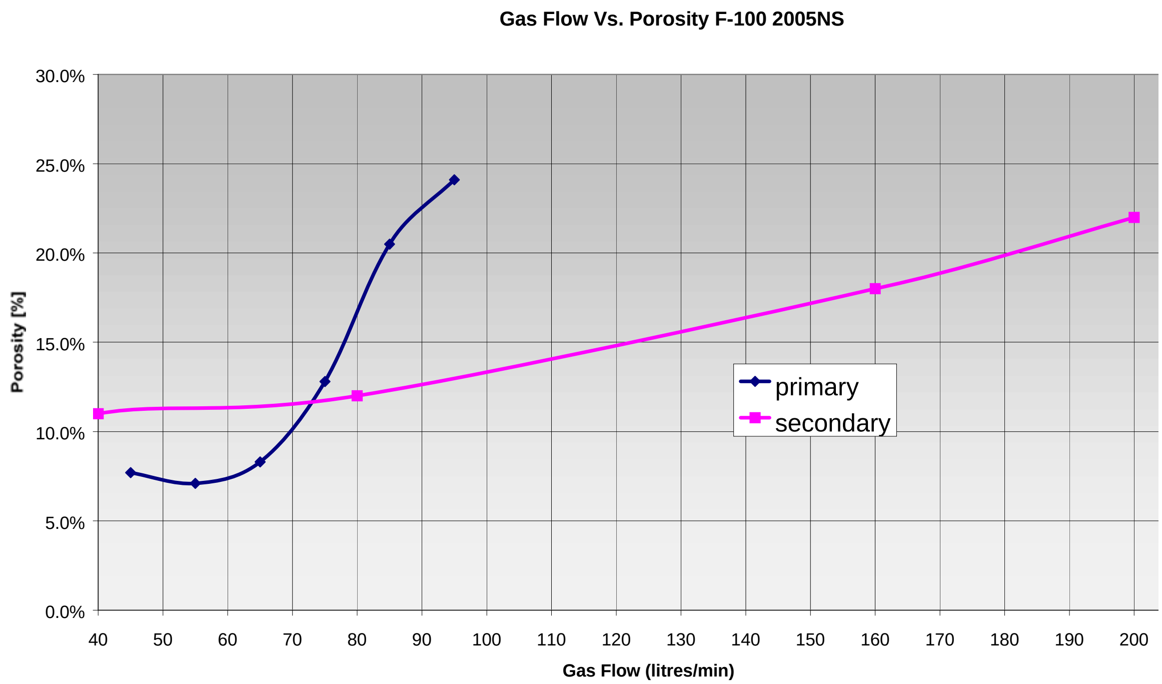



**Figure 2-9 Effect of primary and secondary gas flow on porosity - Diamalloy 2005NS WC-17Co from F-100 gun. Primary gas flow (Ar) 45 lm-1 when varying secondary gas. Secondary gas (He) held at 10 lm-1 when varying primary gas.**

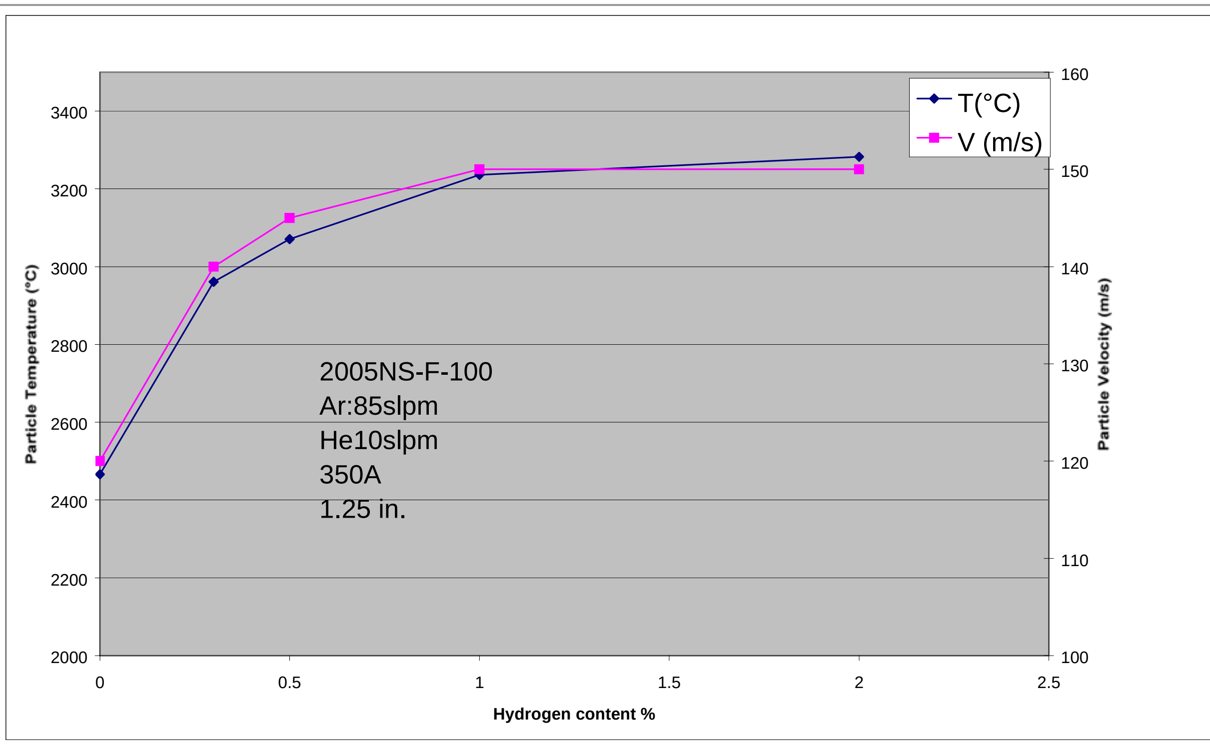



**Figure 2-8. Effect on particle temperature and velocity of hydrogen addition to plasma - Diamalloy 2005NS WC-17Co using F-100 gun.**

## 2.4. Praxair SG-2700 and SM F210 miniature ID guns

The two miniature guns are similar in their capabilities, although they differ in design. The behavior established for the F100 gun (as shown in Figure 2-4 to Figure 2-8) was found to be generally valid for these smaller guns, since they are a very similar design.

**Figure 2-10 Praxair SG-2700 ID gun.**

Most of the testing at Praxair was done with the SG-2700 gun (Figure 2-10), while Sulzer Metco carried out most of their testing with the F210 ID gun (Figure 2-11). The SM-F210 gun is designed with several internal gas feeds that are primarily meant to cool the gun. However, they also serve to help remove overspray. The Praxair 2700 gun requires a separate gas feed for overspray removal.

The temperature velocity profiles of the two guns for typical operating parameters are shown in Figure 2-12 and Figure 2-13. As expected, for the same powder the particle temperatures and velocities for optimal coatings are very similar. This demonstrates that, once the particles leave the gun, the coating quality is determined by their temperatures and velocities, and the coating quality for both guns will therefore be comparable.

**Figure 2-11 Sulzer Metco SM-F210 ID gun.**

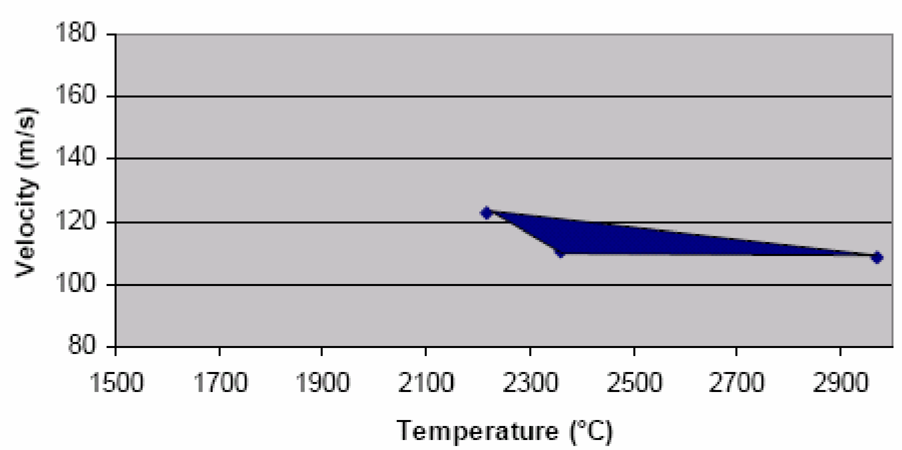



**Figure 2-12. Temperature-velocity profile for SM-F210 gun with 2005NS WC-17Co powder.**

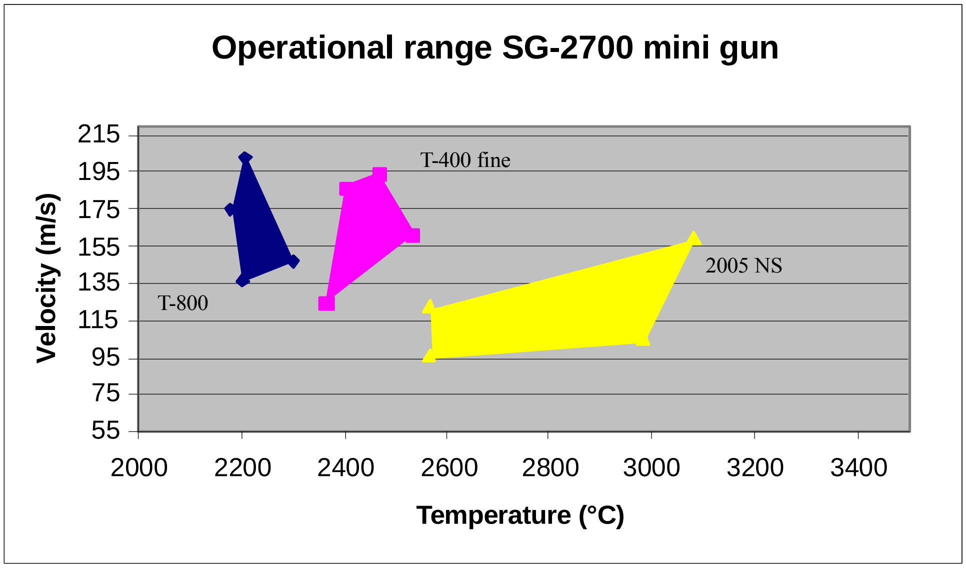



**Figure 2-13. Operational range for the SG-2700 gun with WC-Co (2005NS), T800 (Co-111) and T400 (Co-109-3) fine cut powder as optimized by Praxair.**

Because the two miniature ID guns are essentially similar and the findings apply to both, detailed evaluations were done only with the SG-2700 gun.

Figure 2-13 includes operational ranges for both Tribaloy and WC-Co powders in their optimal ranges. Note that for the SG-2700 gun, Tribaloy powders must be sprayed at lower temperatures, but achieve somewhat higher velocities. This is to be expected since WC is more dense and cannot therefore be accelerated to as high a velocity.

The effects of gas flow changes are shown in Figure 2-14 to Figure 2-16. The major difference between the F-100 and the SG-2700 guns is the rapid falloff in temperature with standoff (i.e. distance from the gun, Figure 2-17). This means that the quality of the coating is much more sensitive to the position of the gun in the ID than it is with the larger gun. Note that, as with the F100, addition of hydrogen gas increases the velocity, but the falloff in temperature is even steeper. There is an inflection point around 1.5” from the gun nozzle, making this a more reliable operating standoff than a shorter distance where the velocity is higher. This in turn defines the location of the back of the gun and hence the minimum diameter that can be sprayed. The gun shaft is 7/8” diameter, so that the distance between the back of the gun and the wall of the tube being sprayed is about 2”. Allowing for adequate clearance between the gun and the tube wall, the gun can spray down to about 2.5” ID.

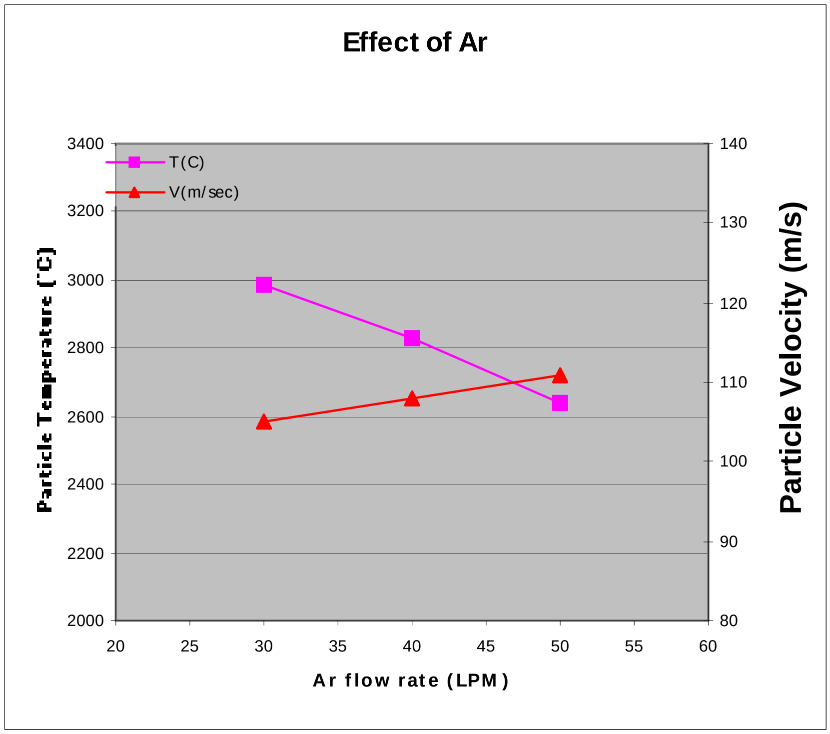



**Figure 2-14. Effect of Ar gas flow on powder temperature and velocity - SG-2700 gun, Diamalloy 2005NS WC-17Co, He flow 20 $lm^{-1}$.**

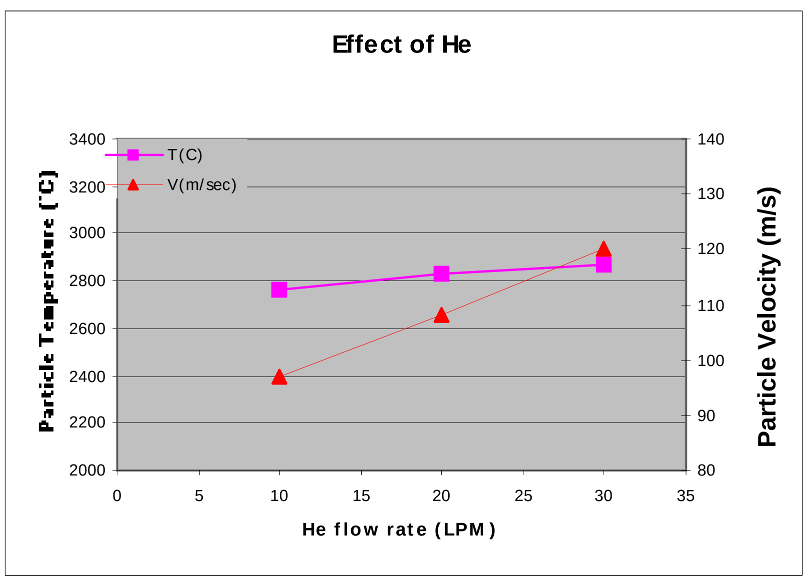



**Figure 2-15. Effect of He gas flow on powder temperature and velocity - SG-2700 gun, Diamalloy 2005NS WC-17Co, Ar flow 40 $lm^{-1}$.**

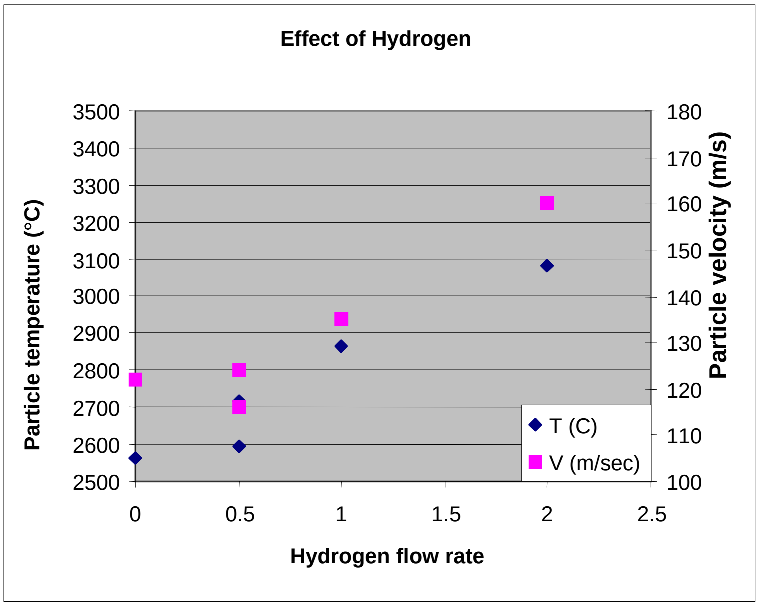



**Figure 2-16. Effect of hydrogen addition on temperature and velocity of particles - SG-2700 gun, Diamalloy 2005NS WC-17Co.**

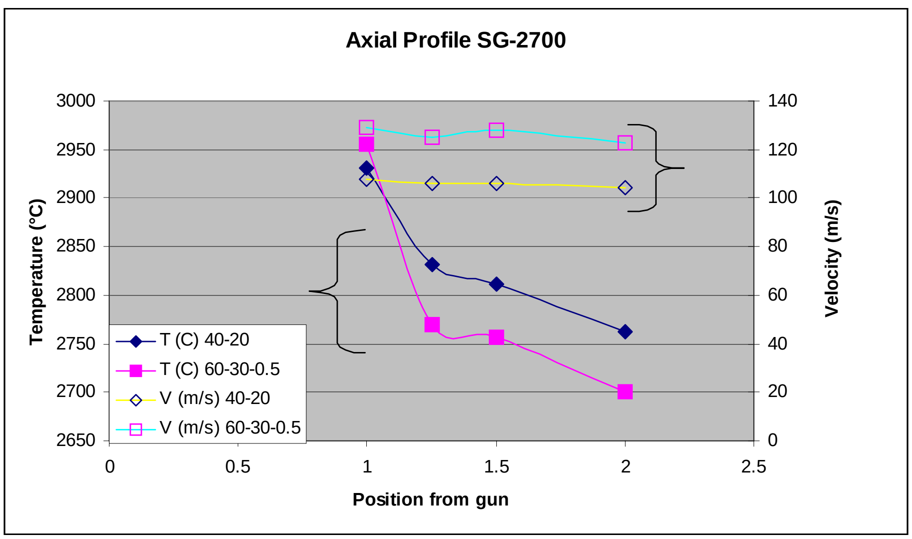



**Figure 2-17. Axial temperature and velocity profiles for the SG-2700 gun, Diamalloy 2005NS WC-17Co. (Numbers in legend are gas flow in lpm for Ar, He and (where indicated) $H_2$, respectively)**

# 3. Coating development and optimization

## 3.1. Coating choice

### 3.1.1. Nanopowders

At the early stages of this project, it was planned to use nanocarbide powders in order to generate high performance coatings. It was expected that using nanocarbide powder would permit a shorter standoff (hence coat smaller IDs) and increase the flowability of the molten droplets, resulting in lower porosity. However, since then, numerous results have been reported showing that WC nanocomposites are far more sensitive to carbide degradation than the standard micro-sized powders traditionally used. The field was reviewed by Salim Bouaricha of NRC-IMI and his review is provided in Appendix 6 and is also available on the HCAT web site [4].

Sulzer Metco has also tested nano-agglomerated powder. For these trials the F-100 internal gun and a 15% nano-agglomerated WC powder were used. The coating results obtained did not show any improvement compared to standard WC-Co materials such as Diamalloy 2005 and Diamalloy 2006. The lowest porosity obtained was 10.2% with a micro hardness of 610 HV0.3, which is soft for a carbide. Based on these results Sulzer Metco recommended proceeding with standard powders rather than with nano-agglomerated powders.

Thus, using nanopowder in plasma spray dramatically increases the degradation of the cermet and makes the process much less reliable. Also, as stated in NRC's April and June 2001 progress reports, the commercial availability of these powders is problematic. **Consequently the decision was made within the group to not use nanocarbide powders.**

### 3.1.2. Standard and small powders

From previous experience in the industry the team chose to evaluate both carbides, which are generally the hardest and most wear resistant of the thermal sprays, and the softer, less wear resistant, but more lubricious Tribaloys, which are used in some actuator and engine applications. The program therefore concentrated on the following materials:

- Tribaloy 400
- WC-Co and WC with other binders. The "self-fluxing" materials appeared to provide lower porosity.
- Other alternatives were evaluated, including WC-CoCr.

Both Praxair and Sulzer Metco carried out in-house spraying and evaluation of a large number of coatings to determine which appeared to offer the best option for IDs. As a result, the materials of Table 3-1 were chosen for optimization and full testing.

**Table 3-1. Optimized ID plasma coatings evaluated in this program.**

| Powder | Chemistry | Comments |
|---|---|---|
| Diamalloy 2003 (Sulzer Metco) | WC-12Co | Fused and crushed. Contains WC and $W_2C$. |
| Diamalloy 2002 (Sulzer Metco) | 55%(WC 12Co) 45%(33Ni 9Cr 3.5Fe 2Si 2B 0.5C) | 55/45 mixture of WC-Co in self fluxing binder |
| Ni-988 (Praxair) | 50%(WC 12Co) 50%(33Ni 9Cr 3.5Fe 2Si 2B 0.5C) | 50/50 mixture of WC-Co in self fluxing binder |
| Co-109-3, Tribaloy 400 (Praxair) | Co-28 Mo-8 Cr-2 Si | Fine cut powder |
| WC-496 (WC-CrC-Ni) (Praxair) | W 20Cr 6Ni 6C | High temperature carbide, good chemical resistance |

# 3.2. Coating optimization

The team agreed that it was desirable for an ID chrome alternative to combine hardness with low porosity in the hope that it would be possible to use the coating without a sealant, just as one can do with HVOF coatings. Therefore coatings were optimized for a combination of hardness (and erosion or abrasion resistance) and porosity.

## 3.2.1. Sulzer Metco

Both NRC and Sulzer Metco used the DPV 2000 spray monitoring equipment to optimize the coatings and to define the conditions for ID spray in terms of the fundamental measures of particle temperature and velocity, and to make it possible to transfer deposition conditions between sites and between different spray equipment.

Sulzer Metco tested a large number of different materials in the course of determining which powders would be optimal for ID coating (Note: microstructural and property data for a variety of tested coatings are provided in Appendix 2):

- There are many types of WC powder for carbide deposition. In an effort to determine which powders could provide the best combination of hardness and porosity, a number of different tungsten carbides were tested (Table 3-2). Diamalloy 2003 WC-12Co material offered the best combination of hardness with reasonably low porosity
- A downselect and test of additional WC materials was made (Table 3-3), from which the Diamalloy 2002 WC-12Co self-fluxing material was finally chosen for its exceptionally low porosity combined with reasonable hardness. (Note that in subsequent porosity measurements made by NRC using the standard methodology developed in this program (see Appendix 1) these coatings were found to be similar in porosity to other plasma spray coatings).

**Table 3-2. Tungsten carbides tested by Sulzer Metco.**

| Powder Designation | Chemical Composition | Particle size range | Manufacturing method |
|---|---|---|---|
| SM 5843 | WC 10Co 4Cr | -45 +11 μm | Sintered and crushed |
| SM 5847 | WC 10Co 4Cr | -53 +11 μm | Agglomerated/Sintered |
| D 2002 | (WC 12Co) 33Ni 9Cr 3.5Fe 2Si 2B 0.5C | -45 +11 μm | Blend |
| SM 5803 | WC 12Co 25(Ni base super alloy) | -45 +11 μm | Blend |
| M 439NS | (WC 12Co) 33Ni 9Cr 3.5Fe 2Si 2B 0.5C | -63 +15 μm | Blend |
| M 439NS-2 | (WC 12Co) 33Ni 9Cr 3.5Fe 2Si 2B 0.5C | -90 +15 μm | Blend |
| D 2003 | $W_2C$/WC 12Co | -45 +5.5 μm | Fused |
| D 2005NS | WC 17Co | -53 +11 μm | Spray dried, sintered |
| D2006 | WC 17Co | -30 +5.5 μm | Spray dried, sintered |
| SM 5810 | WC 12Co | -63 +11 μm | Spherical Composite |
| A 9830 | WC 17Co | -53 +20 μm | Spherical, Agglomerated and densified |
| D 5848 | WC 10Co 4Cr | -45 +11 μm | Spray dried and Sintered |
| D 5826 | WC 17Co | -45 +11 μm | Spray dried and Sintered |

**Table 3-3. DPV controlled and optimized spray trials with the F-210 gun.**

| Run # | Powder | Chemistry | Remark on parameters | Porosity [%] | Macro Hardness [HR15N] | Micro Hardness [HV0.3] | Cracks |
|---|---|---|---|---|---|---|---|
| 10012402-1 | SM 5803 | (WC 12Co) 25(Ni-Based Superalloy) | Ar/He/H2 | 5.3 | 82.2 | 671 | Micro cracks |
| 10012502-1 | D2002 | (WC 12Co) 50(self fluxing alloy), (WC 12Co) 33Ni 9Cr 3.5Fe 2Si 2B 0.5C | Ar/He/H2 | < 1 | 83.9 | 609 | None |
| 10012502-2 | D2002 | " | Less H2 than Run 1 | 2.3 | 81.9 | 707 | None |
| 10012802-1 | 439NS | WC 12Co Self-Fusing Nickel Alloy | Ar/He/H2 | 6.6 | 76.8 | 586 | None |
| 10012802-2 | 439NS | " | More H2 than Run 1 | 1.8 | 77.2 | 528 | none |

### 3.2.2. Praxair

Both T400 and WC-Co coatings were developed and optimized both for powder size and deposition conditions. Gun spray nozzles have been tested for spraying at 45° and 60° angle of incidence to the surface.

In the expectation that smaller diameter powder would produce better coatings, T-400 powder sizes of 325, 400, and 600 mesh (44, 38, and 21 μm) were tested. Powder becomes more difficult to feed as it is made smaller. Praxair experimented with fine silica powder additives to improve flow but concluded that these were not necessary if the conditions (including the secondary carrier gas) were properly optimized. Final optimization concluded that 400 mesh (38 μm) powder gave the best properties. The Design of experiment variables are summarized in Table 3-4.

Tests at different standoff distances showed that the best coatings were produced at a standoff of 2”, but that 1.5” provided a satisfactory coating. Allowing for the size of the gun itself and a small distance between the gun and the inner wall, it was concluded that plasma spray cannot work inside IDs less than 2.5”, even with the miniature guns that are currently commercially available. Above this diameter, however, it is a very rapid deposition method. This means that it will work well for aircraft landing gear, utility actuators, large flight surface actuators and shock absorbers, and other ID applications on aircraft, ships, and vehicles. It will not in general be useful for small flight surface actuators and engine actuators.

**Table 3-4. Design of experiment parameters used for T-400 and WC-Co optimization - Praxair SG-2700 gun. Optimum conditions underlined.**

| Parameters for DOE | Comments |
|---|---|
| Powders: T-400 chemistry, 2 powders: <u>fine</u> and extra fine.<br>WC-Co chemistry, 1 powder: <u>fine</u> | The extra T400 fine powder was difficult to feed through the powder dispenser.<br>The fine T400 powder gave good results. Only fine powder used for WC since extra fine powder did not feed well. |
| Impingement Angle: $45^0$ and <u>$60^0$</u> | Two angles used since some parts will have a blind hole and need a shallower angle to reach farther. |
| Torch to part distance: 1”, 1.5”, <u>2”</u> | A 2” distance is preferred but a shorter distance was also used to allow coating into a smaller diameter than 3”. |
| Surface speed: <u>2400</u>, 3300, 4800 in/min | Lower surface speed preferred for larger parts. A higher surface speed may be preferred for smaller parts. |
| Powder Feed Rate: 10, <u>18</u>, 24, 32, 42 g/min | The lower powder feed rate of 18 g/min is preferred. Higher feed rates may be adequate with higher surface speeds |
| Operating Amperage: 350, 450, 550, 600, 700, <u>800</u> amps | |
| Operating Voltage: 33 to 37 volts | |
| Operating Process gas pressures:<br>Primary Argon: <u>50</u>, 60 psi<br>Secondary Helium: 115, 138, 158, <u>180</u> psi | |
| Carrier Pressure: 40 psi | |
| Coating thickness: 0.010 to 0.012 inch for metallographic and hardness samples, 0.005 to 0.007 inch and ground back to 0.003 inch for surface finish samples, and fatigue bars | |

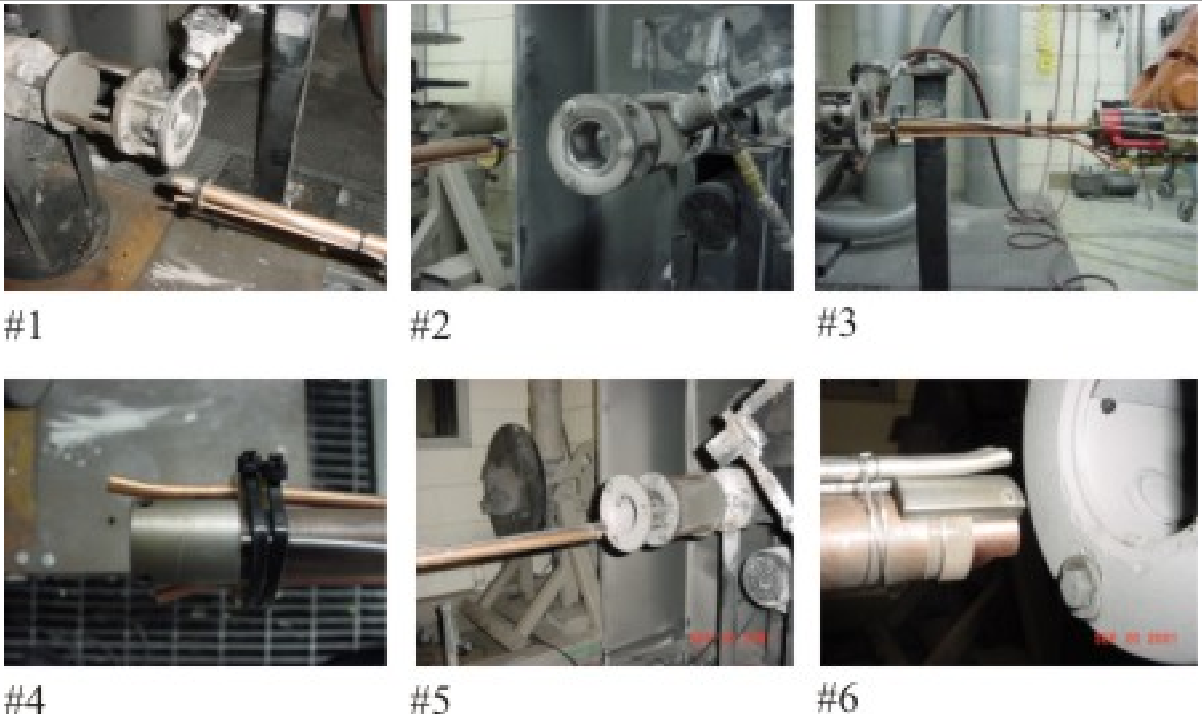


**Figure 3-1 Praxair gun modifications for overspray removal made during coating development.**

Because of an early determination that overspray is a serious issue with the SG-2700 ID gun, Praxair experimented with an additional gas flow nozzle for overspray removal (see Figure 3-1). This arrangement reduced overspray contamination of coatings.

Cross sections for the Praxair/TAFA self fluxing WC coating (Ni-988 powder) under different secondary gas flow conditions are shown in Figure 3-2 to Figure 3-4. These materials show similar hardness, but various microstructures and amounts of porosity.

After development of the Fumespector overspray measurement system at NRC (see Section 5.1), Praxair added a second air nozzle.

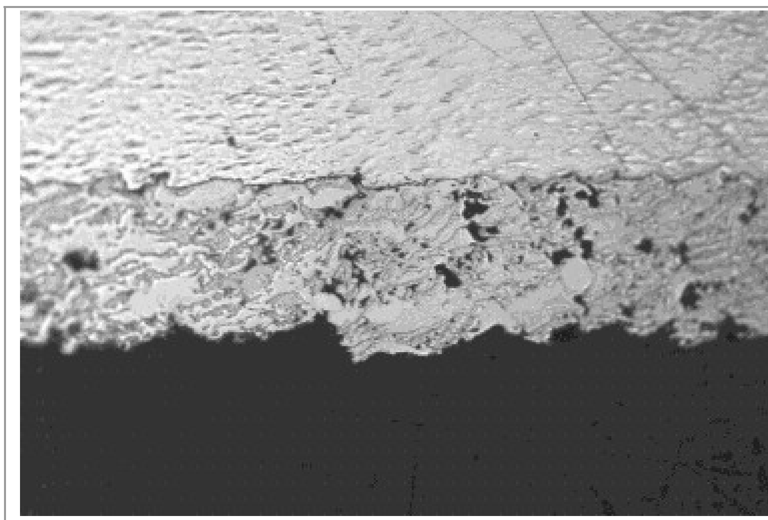


**Figure 3-2 Ni-988 self fluxing coating. Microhardness 765HV**

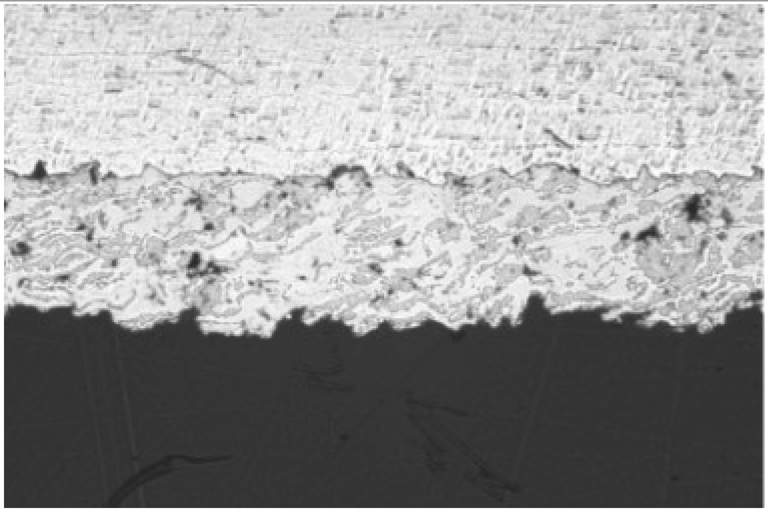


**Figure 3-3    As Figure 3-2 but higher secondary gas and lower porosity.  Microhardness 780HV.**

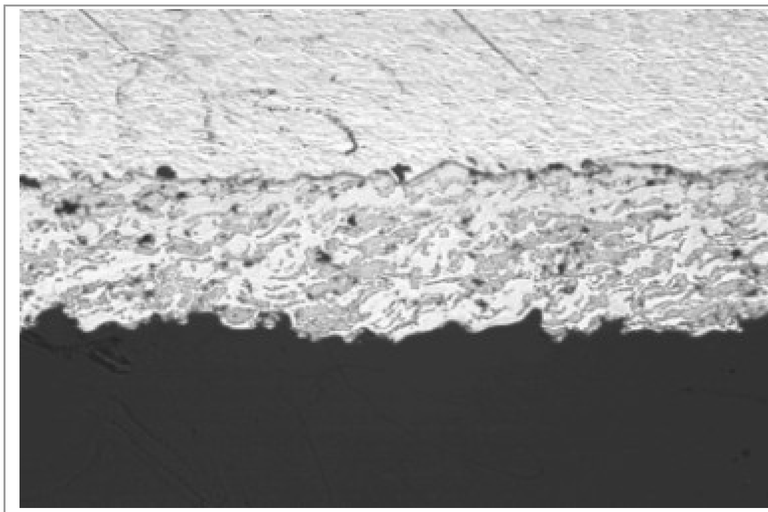


**Figure 3-4    As Figure 3-2, but lower secondary gas; also low porosity.  Microhardness 770HV.**

# 4. Coating Properties and Performance

The test matrix of Table 4-1 was used to evaluate each of the coatings.

**Table 4-1. Material and property tests.**

| Property | Test | Thickness sprayed | Thickness ground | Finish |
|---|---|---|---|---|
| **Coating properties** | | | | |
| Microstructure | Metallography | 0.013-0.015" | no grind | |
| Porosity | Metallography | 0.013-0.015" | no grind | |
| Hardness | Vickers indentation | 0.013-0.015" | no grind | |
| Adhesion | Pull | 0.013-0.015" | 0.008-0.010" | 8 microinch |
| Residual stress | Almen | 0.013-0.015" | no grind | |
| Strain-to-fracture | 4-pt Almen | 0.013-0.015" | no grind | |
| **Coating performance** | | | | |
| Fatigue | Axial tension/tension | 0.005" | 0.003" | 8 microinch |
| Ring-on-disk wear | Ring-on-disk wear | 0.013-0.015" | 0.008-0.010" | 8 microinch |
| Corrosion | Potentiostatic/dynamic | 0.013-0.015" | 0.008-0.010" | 8 microinch |
| Corrosion | B117 salt fog | 0.013-0.015" | 0.008-0.010" | 8 microinch |
| Abrasion | ASTM-G65 (Taber) | 0.013-0.015" | 0.008-0.010" | 8 microinch |

In addition both Praxair and Sulzer Metco carried out their own tests in the course of developing the materials.

## 4.1. Preparation of test specimens

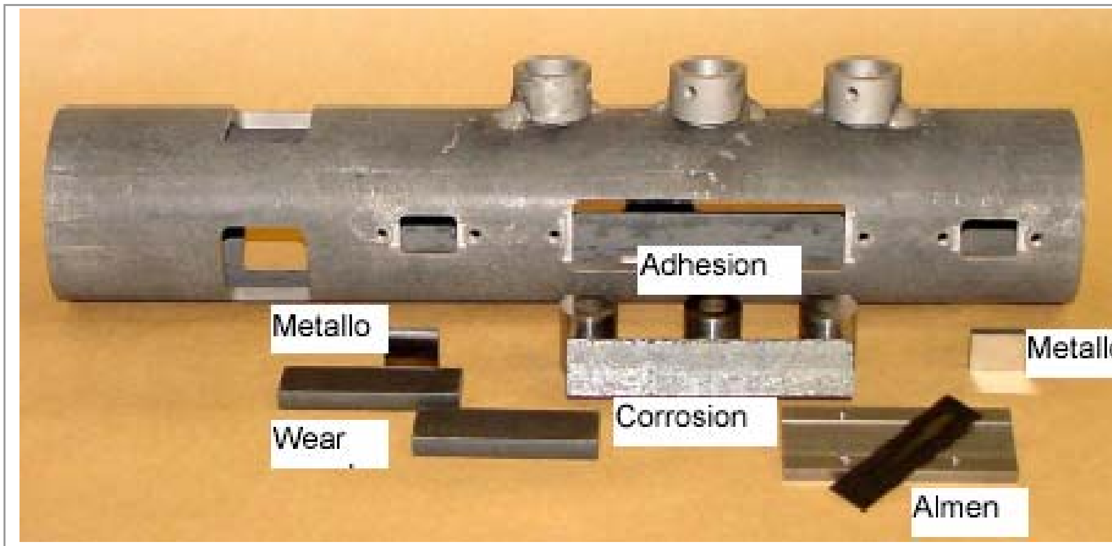



**Figure 4-1 ID specimen coating jig, showing types of specimens.**

All specimens coated with Praxair powders were sprayed at Praxair using the Praxair 2700 gun (see Powder Cross-reference table). All specimens coated with Sulzer Metco powders were coated by Sulzer Metco using the SM210 gun unless otherwise noted in tables or figures. In order to ensure that the coatings were deposited under true ID conditions, yet be able to use standard test specimens, a specimen holder was designed by NRC (Figure 4-1). The holder

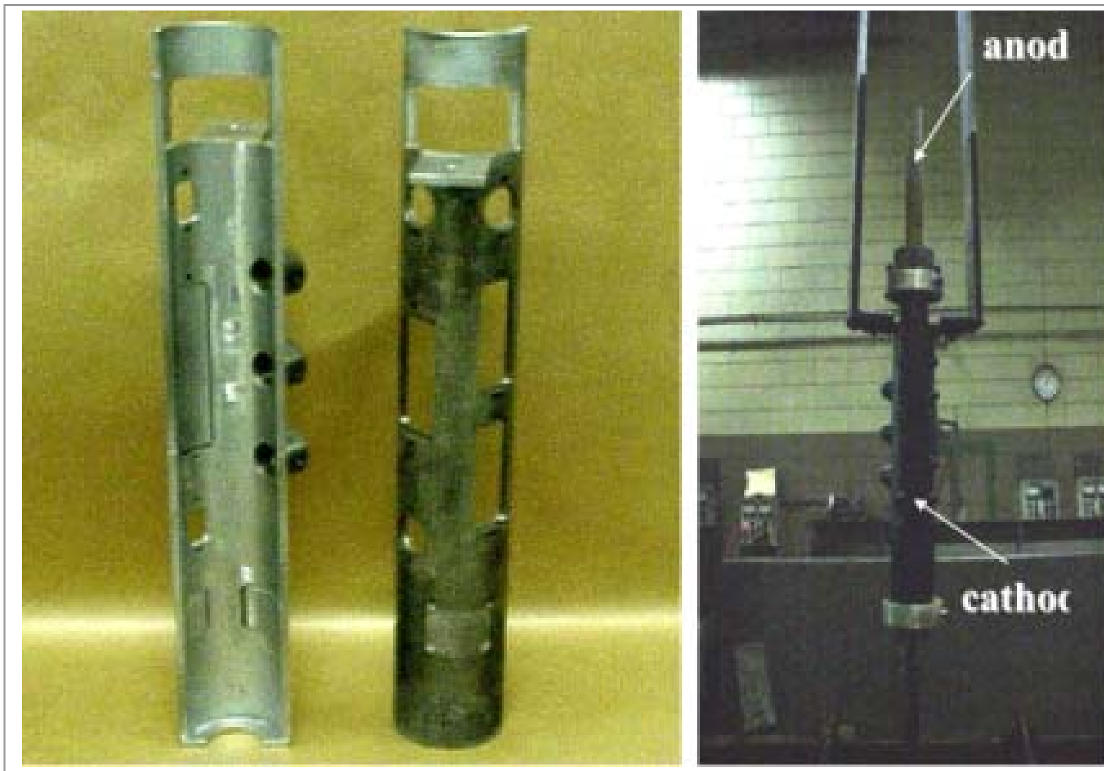



**Figure 4-2 Hard chrome electroplating arrangement.**

consisted of a 3” ID steel tube with holes machined to accept the standard specimen types with their surfaces at the 3” diameter position. The specimens were coated from inside the tube using the ID gun. This holder was reproduced and supplied to both Praxair and Sulzer Metco, as well as to NADEP JAX for electroplating the baseline specimens.

Unfortunately for chrome plating the situation was more complex. Because of the need to coat the specimen surfaces completely and uniformly it was necessary to use stop-off on some areas of the holder. This required the holder to be wax-dipped and the specimen surfaces to be cleaned off prior to plating (as is usually done with chrome plating). The specimen holder was therefore split lengthwise to provide access to the specimen surfaces (Figure 4-2).

Although this holder was designed to accommodate the flat Kb bar fatigue specimens as well as the other specimens, it was found to be impractical for this since they could only be coated one specimen at a time, and the test matrix required sufficient specimens to establish a fatigue curve. To solve this problem a jig was made specifically for these specimens (Figure 4-3) in which eight specimens were placed around a circle with their gauge surfaces at a 3” ID. They were then coated using a plasma gun inside this ID. This jig was made by Praxair, used to coat their fatigue specimens, and then sent to Sulzer Metco for their fatigue coatings. A similar jig was fabricated at NADEP JAX for chrome plating.

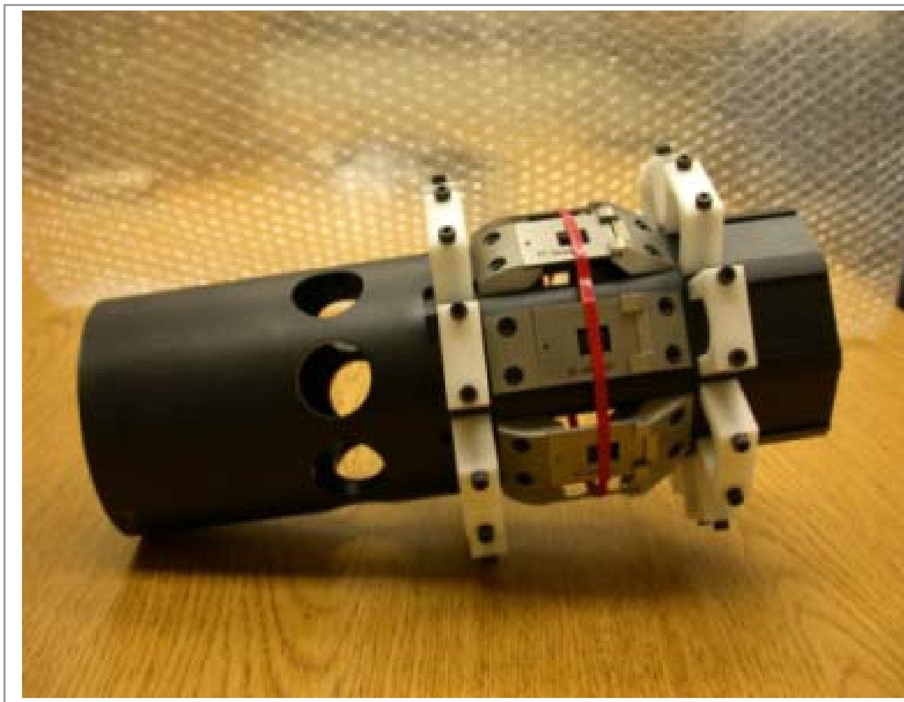


**Figure 4-3 Jig for ID spraying eight fatigue specimens at a time (developed by Praxair).**

Except for strain-to-fracture data (related to coating integrity), which were taken from coatings deposited on standard Almen strips, all data were taken from coatings deposited on 4340 high strength steel of 230 ksi yield and 280 ksi UTS. This is typical of the steel used for landing gear, which is a higher tensile strength than is typical for 4340 steel used in hydraulic actuators. The use of this material permits the data to be compared with our extensive database for landing gear steels.

## 4.2. Structure and porosity

### 4.2.1. Test methods

It rapidly became apparent that measurements of porosity made by the different team members using their own standard methods yielded completely different results. When porosity was measured in the SEM on metallographic cross sections of the same coatings prepared by the standard polishing techniques used at Praxair and NRC-IMI, the results of Table 4-2 were obtained. Clearly, the polishing technique has a major effect on the measurement of porosity. NRC evaluated this problem and developed a standard test method that all team members could use for future evaluations.

**Table 4-2. Porosity comparison for T-400 using SEM for two different polishing techniques.**

| | % Porosity | |
|---|---|---|
| Sample | IMI | Praxair |
| 5-3 | 14.3 | 5.6 |
| 12-4 | 7.5 | 0.1 |
| 12-6 | 7.5 | 0.5 |
| 13-2 | 7.9 | 0.4 |
| 14-1 | 7.2 | 1.9 |
| T-800 (60-30) | 10.9 | |

To understand the nature of the problem and obtain a reliable porosity measuring method that could be used by all team members, NRC carried out evaluations using different mounting materials and polishing methods (Table 4-3, Figure 4-4, Figure 4-5). Repolishing the Bakelite mounted specimens revealed the porosity to be significantly higher than as first measured, probably because the NRC polishing method caused less smearing. (T-400 is likely to be particularly sensitive to smearing.) Use of vacuum epoxy made an even more significant change. It is believed that this is because the Bakelite does not fill the pores, allowing material to smear over them and reduce their apparent size. Vacuum impregnation ensures that the pores are filled (which can be seen in the SEM).

The final standard polishing procedure for porosity measurement is given in Appendix 1.

**Table 4-3. Detailed comparison of porosity measurements made on two samples using four mounting methods.**

| Mounting | Bakelite | | Vacuum-epoxy | |
|---|---|---|---|---|
| Polishing technique | Praxair[1] | IMI[2] | IMI[1] | IMI[2] |
| Sample | %Porosity (standard deviation) | | | |
| 5-3 | 5.6 (3.7) | 11.0 (2.6) | 14.3 (3.1) | 10.0 (1.7) |
| 12-4 | 0.1 (0.1) | 3.5 (0.5) | 7.5 (1.9) | 7.6 (0.8) |

[1] Initial results – measurement made at a magnification of 500X using 10 fields of view
[2] Measurements made after all samples were repolished using a magnification of 500X using 5 fields of view

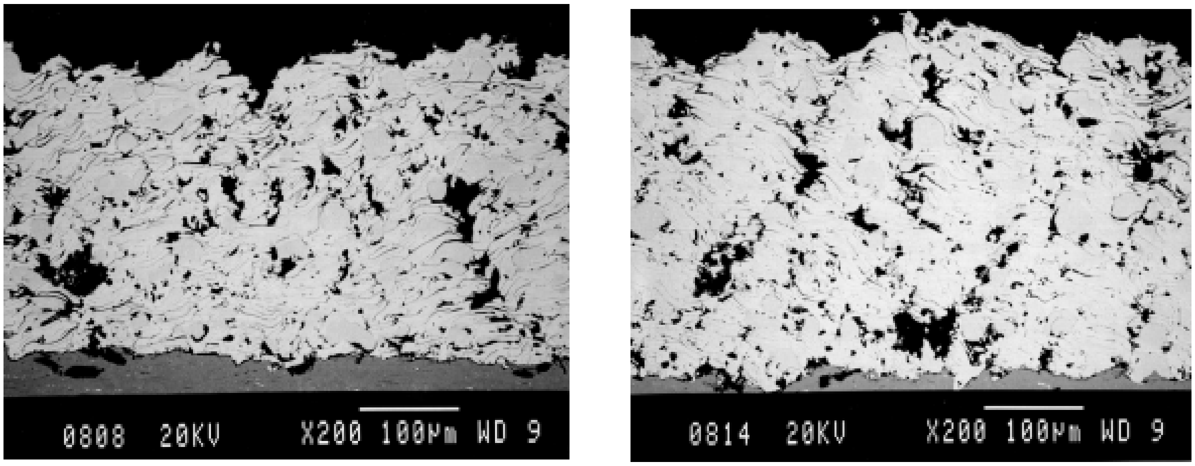



**Figure 4-5 Microstructure of Sample 5-3 taken at 200x. a) cold-mounted under vacuum (10.6%); b) hot-mounted in Bakelite (9.7%).**

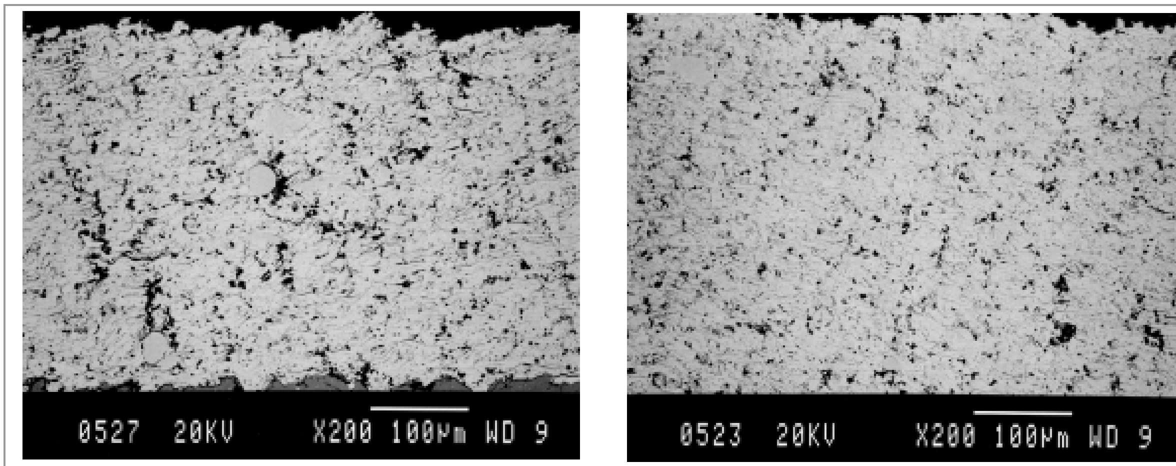



**Figure 4-4 Microstructure of Sample 12-4 taken at 200x. a) cold-mounted under vacuum (6.4%); b) hot-mounted in Bakelite (2.7%).**

### 4.2.2. Results

Most of the coatings showed porosity in the range of 6 – 10%, which is typical for plasma sprays (the porosity of HVOF coatings is much lower, typically <1%). Most plasma spray coatings and hard chrome used in hydraulics are sealed with a polymer sealer (applied either by vacuum impregnation or by wipe on/wipe off). However, users do not know what porosity level is required to eliminate the need for a sealer. Although the coating materials and deposition conditions were chosen to give as low a porosity as possible, it was not possible to approach the porosities typical of HVOF or EHC. Therefore it is likely that, at least for gas-over-fluid systems such as landing gear, it will be necessary to use a sealer.

The measurements of Table 4-4 were made by NRC on the materials produced by Sulzer Metco and Praxair, using the porosity measurement methods described in Appendix 1. Note that, although the initial choice of the self-fluxing materials was based in part on their low porosity in vendor tests, when the porosities were measured using the standards developed by NRC, these coatings were quite similar in porosity to the other coatings.

**Table 4-4. Porosity and carbide content of ID plasma spray coatings.**

| Coating | Powder | Measurement | Porosity | Stdev | vol% carbide | Stdev |
|---|---|---|---|---|---|---|
| WC-Co self flux | D-2002 | %pores | 6.3 | 0.6 | | |
| WC-Co self flux | D-2002 thick | % pores | 10.0 | | 19.9 | 2.5 |
| WC-Co self flux | Ni-988 | % pores | 7.5 | | 17.9 | 1.6 |
| WC-12Co | D-2003 | % pores | 6.0 | 0.7 | | 0.7 |
| T400 | T-400 | %pores+oxide | 7.2 | 1.3 | | 1.3 |
| Ni5Al | D-4008 | %pores | 4.5 | 0.5 | | 0.5 |
| Ni5Al | D-4008 | %oxide | 3.4 | 0.2 | | 0.2 |

*Note: Ni5Al is a relatively soft material generally used for build-up. It has been used purely for comparison.*

The microstructure of EHC deposited at NADEP-JAX is shown in Figure 4-6. Note that this particular specimen shows two layers apparently made under somewhat different conditions. The light area at the bottom is the substrate. Next to the substrate is a 110µm (0.004") layer that shows the typical microcracked structure. At the top of this is a faint, but distinct interface, above which the coating is almost crack-free.

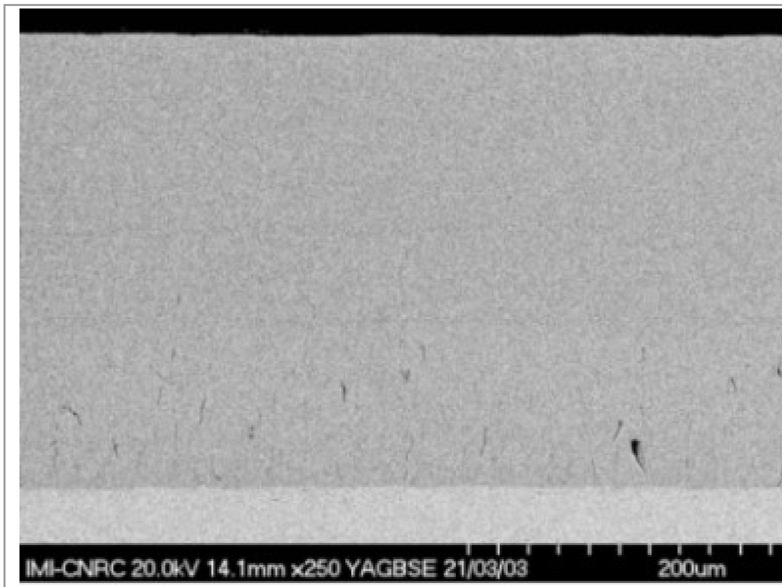



**Figure 4-6 Cross sectional microstructure of EHC (lower area substrate).**

WC-12Co is shown in Figure 4-7, with a higher magnification picture inset. It shows distinct carbide grains within the Co matrix, and significant porosity.

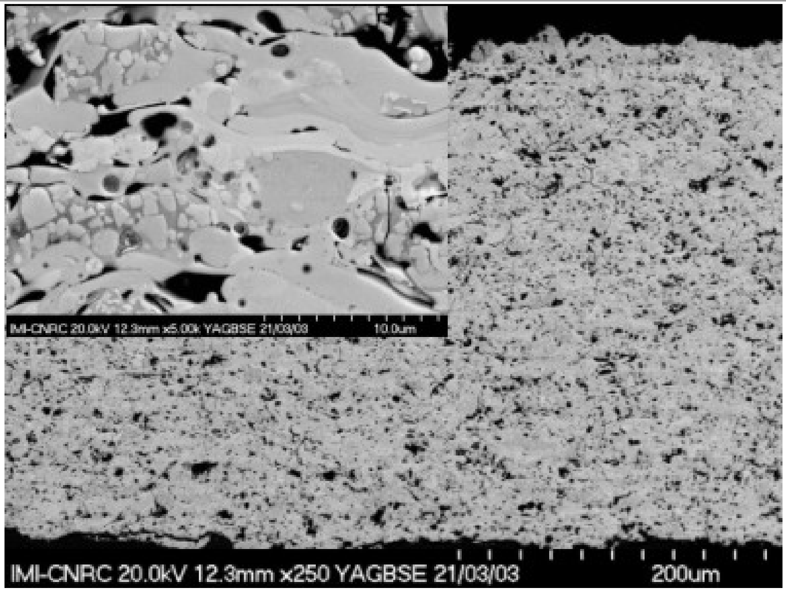



**Figure 4-7 Cross sectional microstructure of WC-12Co (D-2003).**

Figure 4-8 and Figure 4-9 show the self-fluxing carbides from Sulzer Metco and Praxair respectively. At the right of the figures are maps of pores and carbides for a region of the coating. Note that there are fewer carbides than in WC-12Co (Figure 4-7), as expected, and that the two materials are very similar.

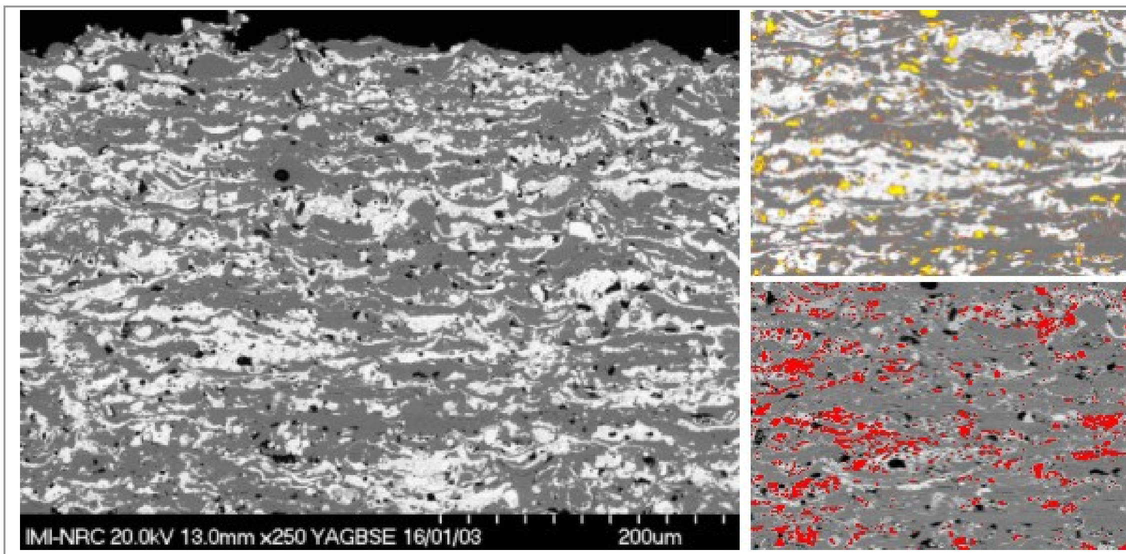



**Figure 4-8 Cross sectional microstructure of WC-Co self fluxing (D-2002). Right – map of porosity on a typical area (yellow), WC (red)**

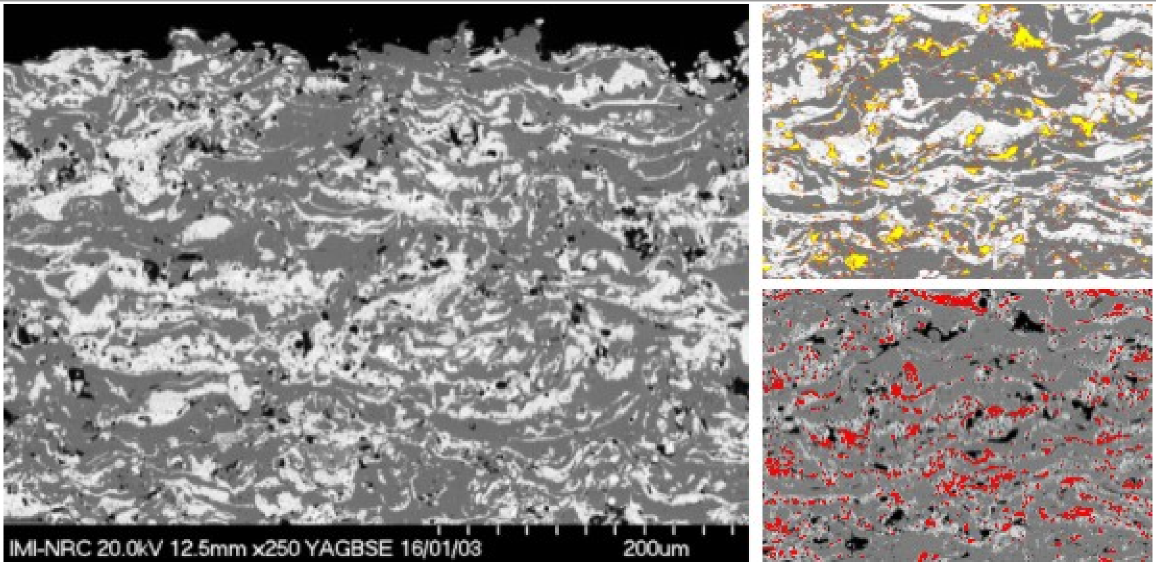



**Figure 4-9 Cross sectional microstructure of WC-Co self fluxing (Ni 988). Right – map of porosity on a typical area (yellow), WC (red)**

Tribaloy 400 is a very different structure (Figure 4-10) since it contains no carbides. Instead, it is hardened by a hard, intermetallic Laves phase. HVOF Tribaloys tend to be much more porous than carbides, but the plasma spray materials have similar porosities.

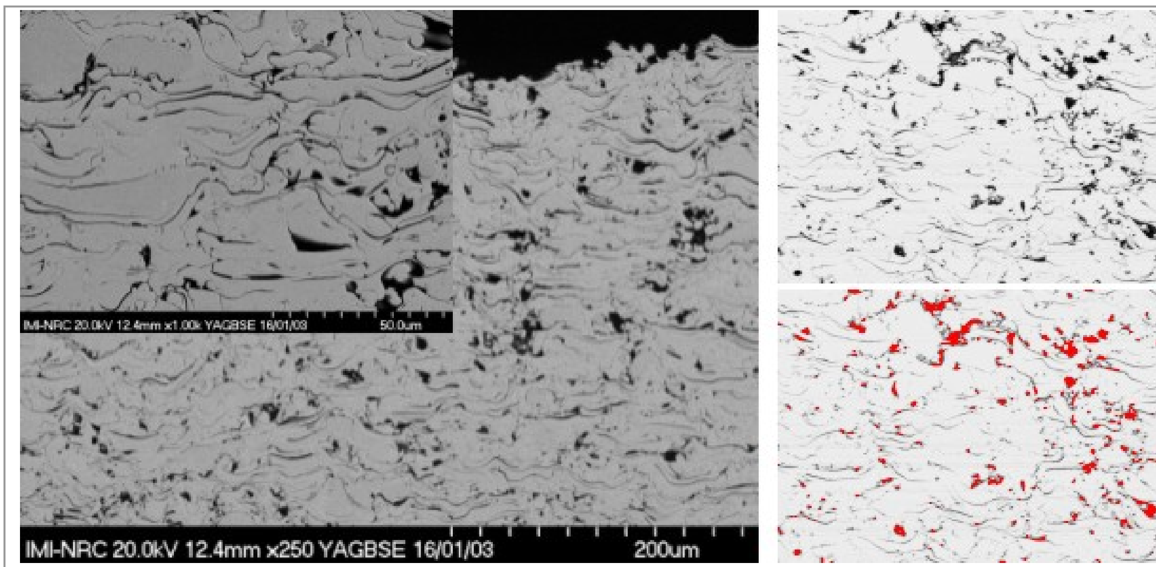



**Figure 4-10 Cross sectional microstructure of T400. Right – porosity map with porosity in red.**

### 4.2.3. Comparison between ID and OD deposition

One set of specimens of the coatings deposited for corrosion testing were deliberately deposited in an OD geometry using the deposition conditions developed for ID coating. This allowed us to compare the structure of the coatings to determine if ID coatings have a lower quality (e.g. higher porosity). Comparisons are shown in Figure 4-11 to Figure 4-14.

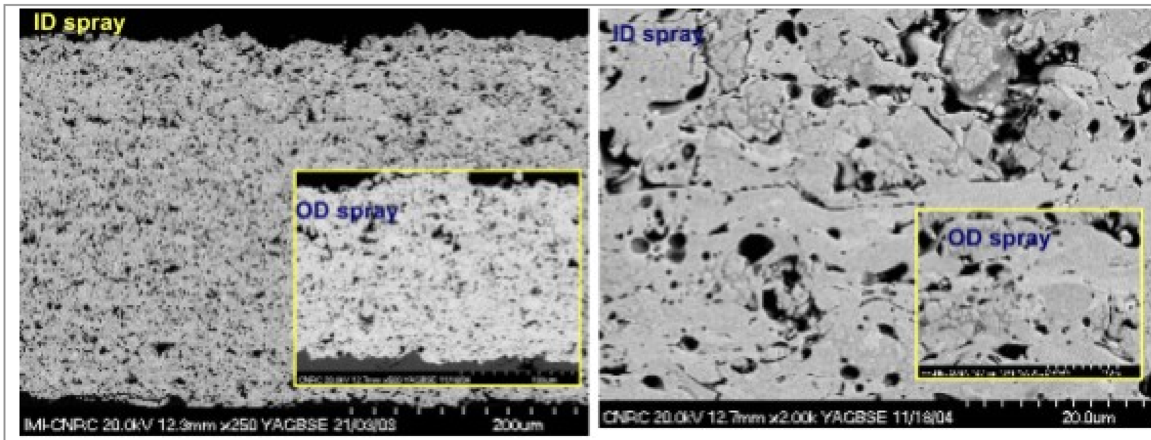



**Figure 4-11 Comparison of ID spray with OD spray microstructure (inset) for WC-12Co (D-2003). Insets are same magnification as ID spray pictures.**

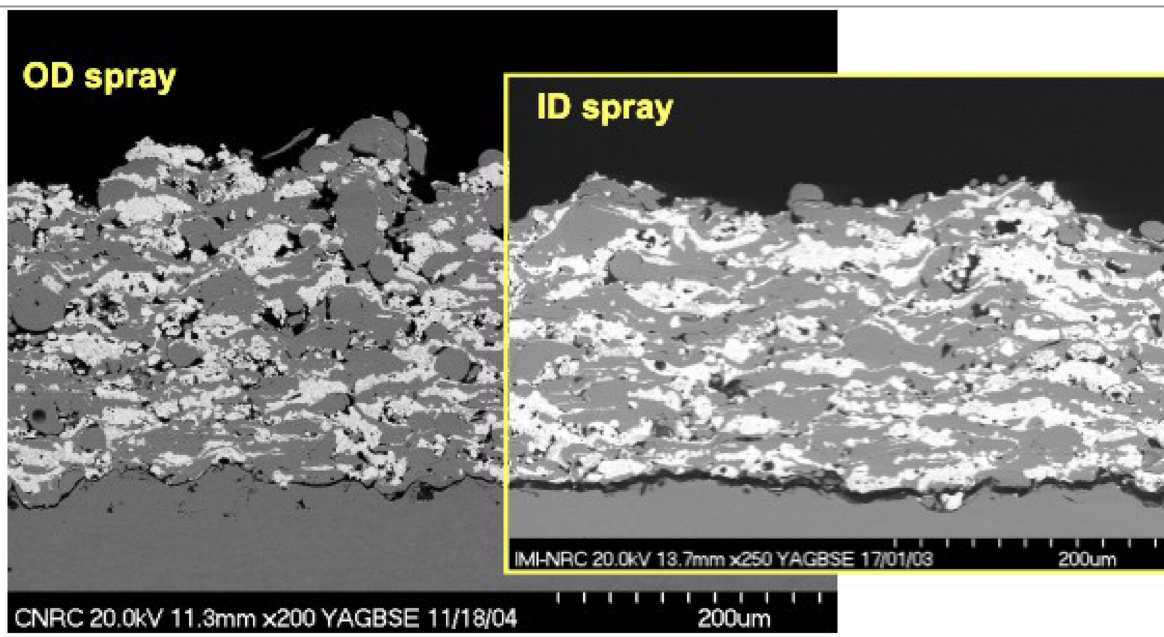



**Figure 4-12 Comparison of ID spray with OD spray microstructure for WC self-fluxing (D-2002). Pictures are same magnification.**

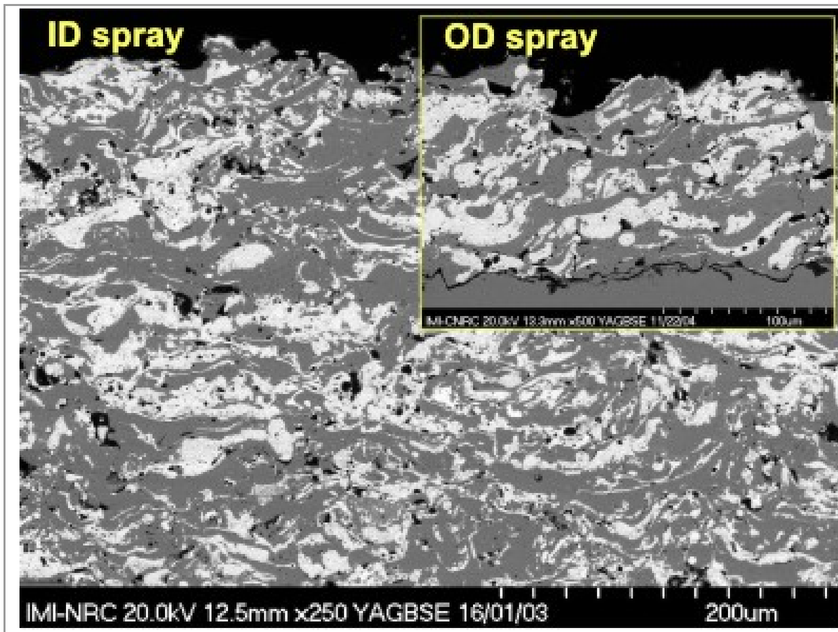



**Figure 4-13 Comparison of ID spray microstructure with OD spray (inset) for WC self-fluxing (Ni-988). Pictures are same magnification.**

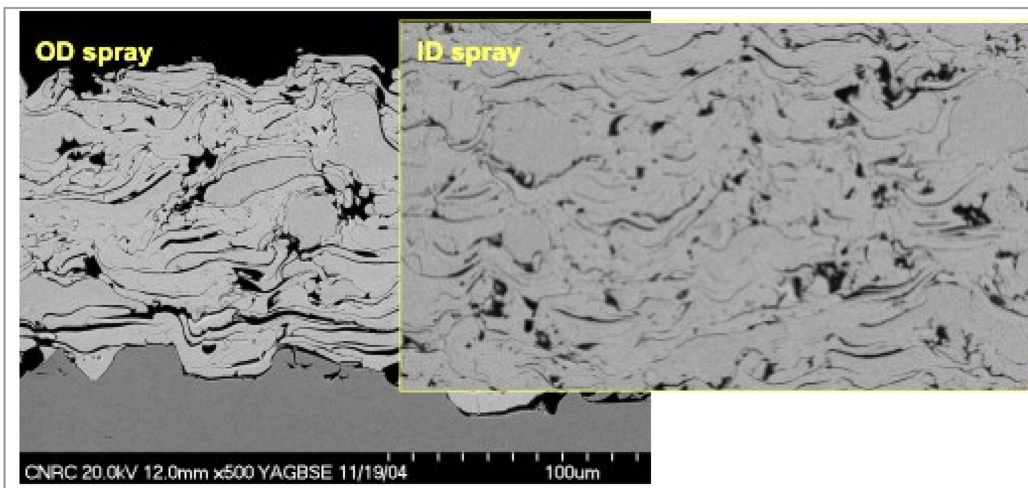



**Figure 4-14 Comparison of ID spray with OD spray microstructure for T400 (Praxair**

In all cases the microstructures and porosities are very similar whether the material is produced in an ID or an OD configuration. This shows that, provided the overspray is properly removed,

coating quality is essentially the same for ID as for OD spray.

## 4.3. Hardness

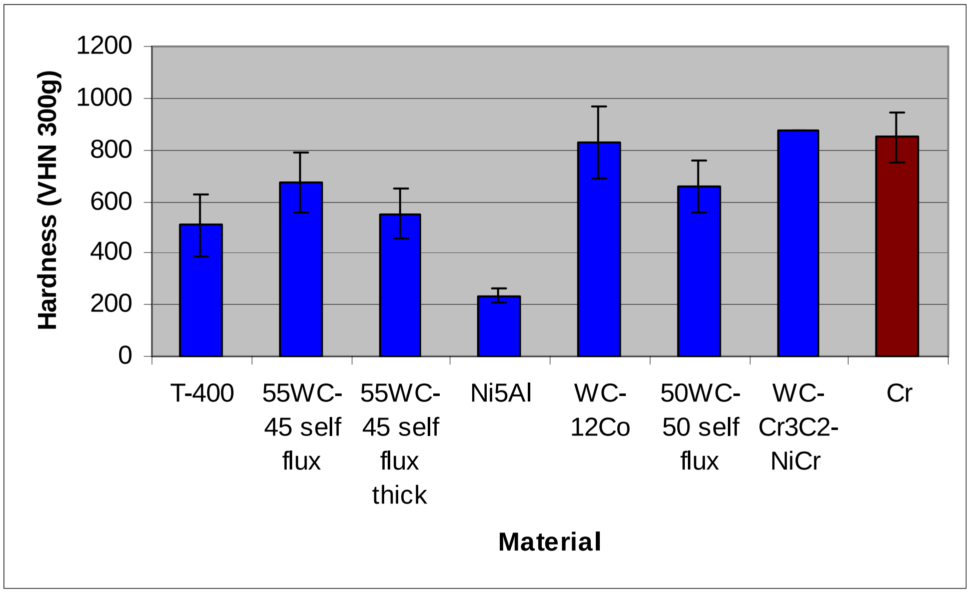



**Figure 4-15 Vickers hardness of plasma spray coatings and EHC.**

Coating hardness is shown in Figure 4-15. The Ni5Al is not intended to be an ID chrome alternative, but was included as an example of a soft, adherent bond coat typically used for building up worn surfaces. WC-12Co and WC-$Cr_3C_2$-NiCr both have hardness equivalent to that of hard chrome (the hardness of the latter was the reason for Praxair's choice of this material). The two self-fluxing materials are equivalent within the error bars. The Tribaloy coatings were expected to be softer. (Note that Ni5Al is not a wear coating, but is a material used for build-up.)

## 4.4. Adhesion

Adhesion was measured by the standard glue pull test (ASTM C633), and the results are shown in Figure 4-16. The adhesion of hard chrome is very high because of its metallurgical bond with the substrate, and as is usually the case the chrome plate did not disbond. This means that the bond strength exceeded that of the glue (nominally 8,000 psi), but the actual bond strength could not be measured. Only Ni5Al matches this bond strength (or at least exceeds the bond strength of the glue). The 50/50 self-fluxing material is close in bond strength. Note that the bond strength of the self-fluxing material presumably has more to do with deposition conditions than with chemistry, since the two self fluxing coating materials were deposited using different guns and different optimized deposition parameters.

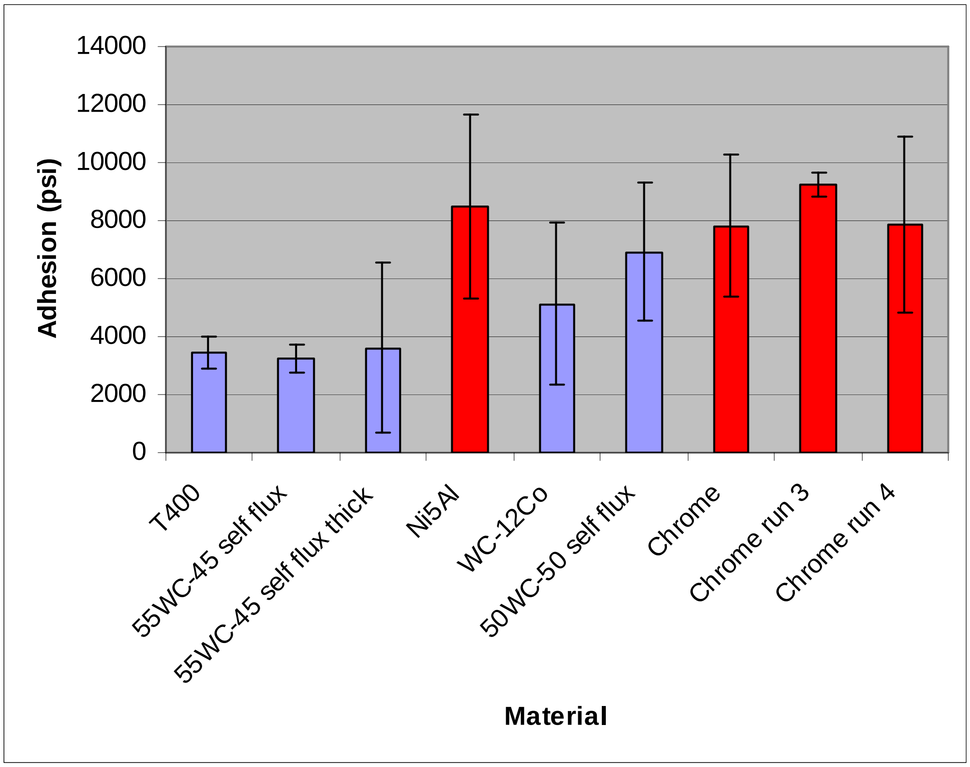



**Figure 4-16 Adhesion (bond) strength of plasma spray coatings and EHC. (Glue failure bonds in red, coating cohesive and adhesive failures in blue.)**

# 4.5. Coating integrity

## 4.5.1. Test methods

HCAT has found that an important issue in the use of thermal spray is coating integrity, which is defined as the ability of the coating to withstand without spalling the strains that the component will see in service. NRC-IMI developed a new capability for evaluating coating integrity and measuring strain-to-failure.

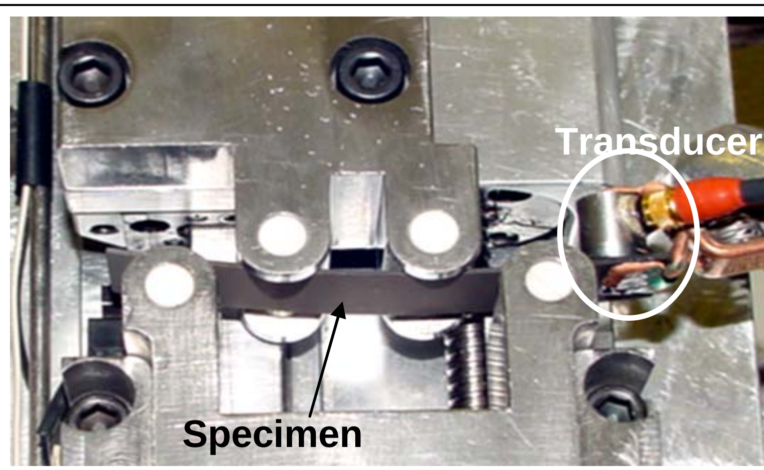



**Figure 4-17. Four point bend test apparatus.**

The system was designed as a four point bend apparatus (Figure 4-17). For reasons of cost and simplicity the specimen was an Almen N strip coated on one side. The strip is inserted into the equipment with the coated side downwards, resting on the outer cylinders. The upper cylinders press onto the top of the specimen, creating uniform bend stress over the central area. A microphone picks up

sound emissions, permitting the measurement of number and intensity (energy) of acoustic events, which in turn can be related to the initiation and growth of cracks.

### 4.5.2. Comparative materials

Before using the test method on the plasma sprayed materials it was first applied to plasma spray and HVOF materials whose integrity performance is known – plasma sprayed Ni5Al (the standard plasma sprayed build-up material) and HVOF WC-17Co. The acoustic data are shown for these comparative materials and an initial plasma spray Diamalloy 2002 WC-Co self fluxing coating. Because Ni5Al is ductile it would be expected to show the lowest acoustic emission and little or no cracking. HVOF WC-17Co, on the other hand, has been found to be a relatively brittle material that begins to crack at a relatively high load. This is clearly seen in Figure 4-18 and Figure 4-19. The behaviour of the D-2002 ID material is intermediate between the Ni5Al and the WC-17Co, but closer to the former.

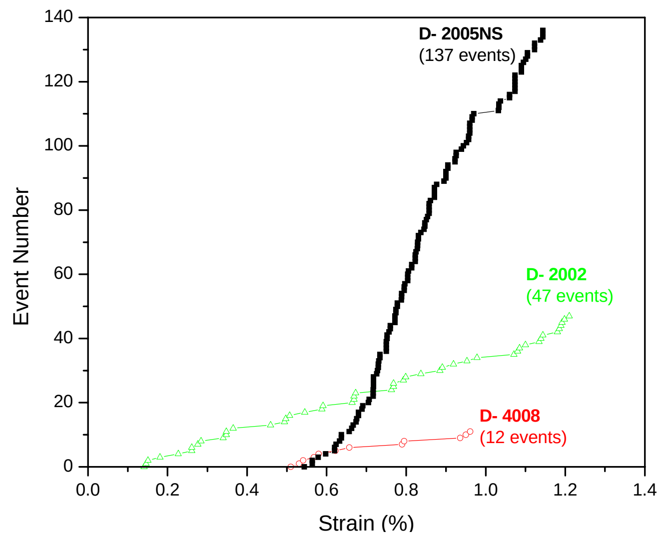



**Figure 4-18. Number of events vs strain – comparative test specimens. D2005NS, HVOF WC-17Co; D-4008, APS Ni5Al; D-2002, APS WC-Co self fluxing.**

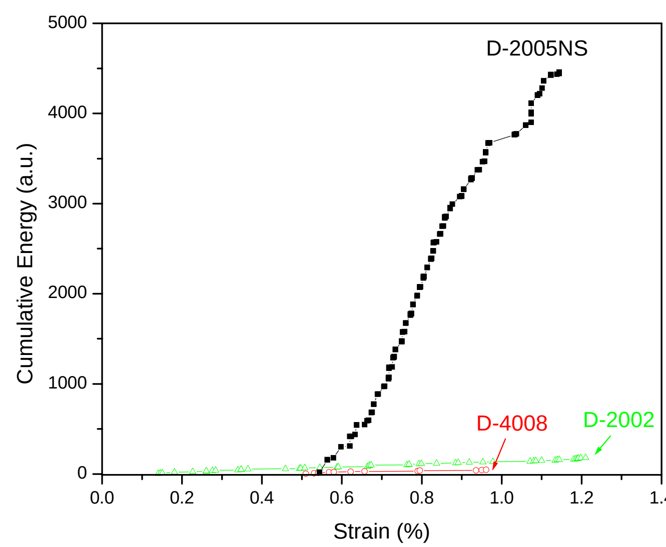



**Figure 4-19. Cumulative energy vs strain – comparative test specimens.**

### 4.5.3. ID plasma spray materials

Table 4-5 summarizes the data obtained from plasma spray and chrome plated coatings, with HVOF WC-Co and plasma spray Ni5Al for comparison.

**Table 4-5. Summary of 4-point bend acoustic emission data.**

| Sample Identity | Coating thick-ness | # Events | Onset of Cracking (ε%) | Mean Energy per event (a.u.) | Cumulative Energy (a.u.) | Onset of Spalling (ε%) |
|---|---|---|---|---|---|---|
| **Chrome-1 setup** | 0.013 – 0.015” | 2427 | 0.142 | 3.8 | 9,199 | |
| **Chrome-2 setup** | 0.013 – 0.015” | 747 | 0.168 | 13.6 | 10,174 | |
| **Chrome-3 production** | 0.013 – 0.015” | 421 | 0.081 | 14.5 | 6,126 | |
| **Chrome-4 production** | 0.013 – 0.015” | 1108 | 0.092 | 14.2 | 15,773 | |
| **D4008 Ni5Al** | 0.013 – 0.015” | 12 | 0.5 | 4.9 | 100 | |
| **D2005NS WC-17Co HVOF** | 0.005” | 137 | 0.55 | 20 | 4,500 | |
| **D2002-a1 55%WC-45% self fluxing** | 0.015 – 0.016” | 53 | 0.118 | 17.6 | 934 | 0.2 |
| **D2002-a2** | 0.015 – 0.016” | 83 | 0.045 | 20.5 | 1,704 | 0.57 |
| **D2002-b3** | 0.008 – 0.009” | 47 | 0.141 | 3.8 | 180.2 | |
| **D2002-b4** | 0.008 – 0.009” | 42 | 0.202 | 4 | 168.4 | |
| **Ni988 (1) 50%WC-50% self fluxing** | 0.013 – 0.015” | 38 | 0.452 | 3.9 | 148 | |
| **Ni988 (2)** | 0.013 – 0.015” | 1 | 0.797 | 4 | 4 | |

T400, Praxair self fluxing (Ni988) and thin Sulzer self fluxing (D2002) materials do not spall up to a maximum deformation of 1.4%. However, the thick D2002 coatings do spall, which is shown as a rapid rise in acoustic emission (AE) followed by a plateau (see Figure 4-20). From the table, the thermal spray coatings showing the greater propensity for spalling have, in general, a higher average energy per AE event, and a higher cumulative energy. This is what is expected for brittle materials, which tend to fail by rapid propagation of cracks through large distances. However, these simple measures alone are not predictive of spalling behavior, since the chrome plate, which does not spall, also has a high energy per event and a larger cumulative energy. In

order to use AE data predictively it will be necessary to acquire a better understanding of the correlation of the data with the nature of the failure mechanism. This is being done under an HCAT Process Mapping test program.

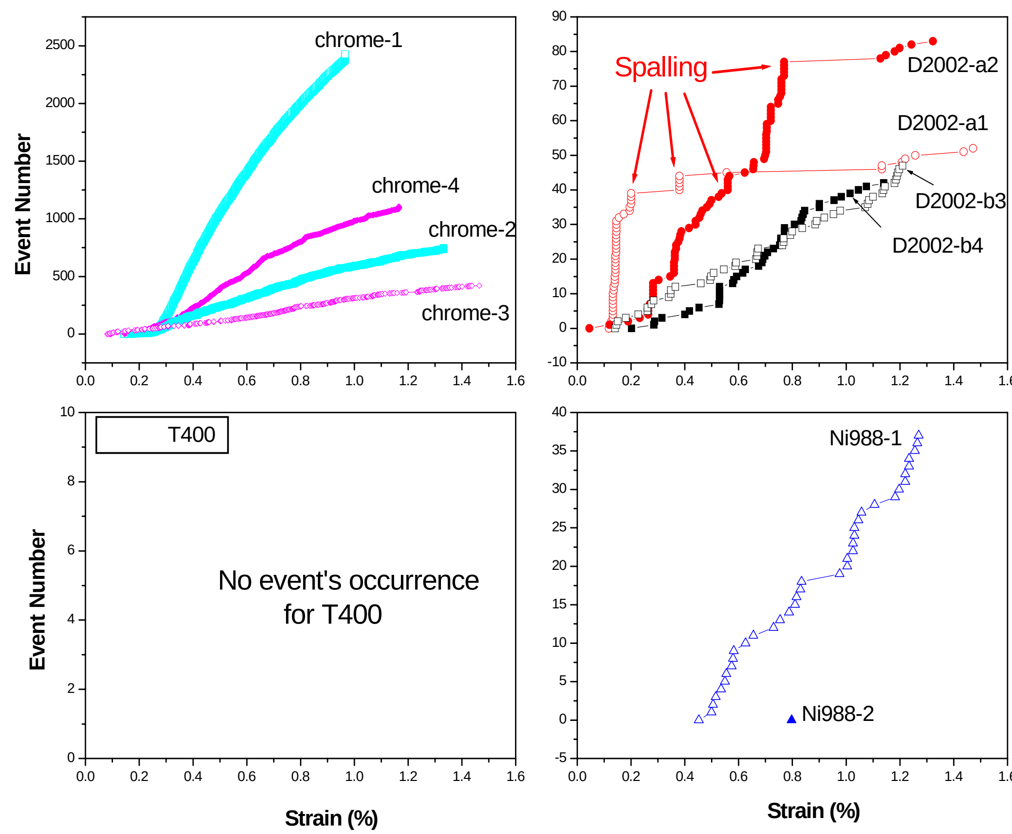



**Figure 4-20. Number of acoustic events vs strain for baseline EHC and plasma spray ID coatings.**

Data on the number of AE events for ID plasma sprays is shown in Figure 4-20. Surprisingly, the T400 coatings show no AE at all (i.e. T400 does not crack), while the Ni-988 and thin D2002 have low AE. Note also that the 50% metallic Ni-988 material shows similar behavior to the thinner 45% metallic D-2002 – i.e. the more metallic materials are indeed more ductile, as is expected. On the other hand, hard chrome coatings have a high number of AE events, while the thick D2002 coatings spall at low applied strain, after emitting about only 40 to 50 AE events.

From the acoustic emission point of view, the extent of damage undergone by bent coatings is better described by the loudness of the AE events, which measures energy release in a cracking event. The energy released is thought to correspond to the degree of resistance to crack formation. Cumulative energy is defined by the sum of released energy per event during the whole test. Figure 4-21 shows the cumulative energy vs. strain for the deformed coatings. The Ni-988 only accumulated a small amount of energy during the test and presented an average energy per event as small as 4 a.u. (arbitrary unit).

The D-2002 coatings were sprayed separately in two groups, the only difference between them being their thickness. For the range of applied strain, thick (0.015 – 0.016”) D-2002 coatings spalled while thin ones (0.008 – 0.009”) did not. As Figure 4-20 and Figure 4-21 show, despite a similar number of events, thick coatings exhibit a higher cumulative energy than thin ones. At the moment of spalling thick coatings have released about 4 to 5 times the energy released by thin coatings. The energy per event, plotted in Figure 4-22 as a function of strain, shows that thin coatings presented a single uniform energy distribution with no high-energy events, reflecting a similar damage mechanism throughout the strain experiment. However, thick coatings display two energy distributions – a large number of weak (< 20 a.u.) and a small number of strong (> 20 a.u.) events. Moreover, the energy of strong events increases until it reaches a maximum value, at which spalling occurs. Each of the thick samples exhibits two spalling sequences during its deformation as indicated by arrows in Figure 4-20 and Figure 4-21. Figure 4-23 shows these specimens after testing. Note that each has 2 large cracks, corresponding to the two major AE energy release peaks in Figure 4-22.

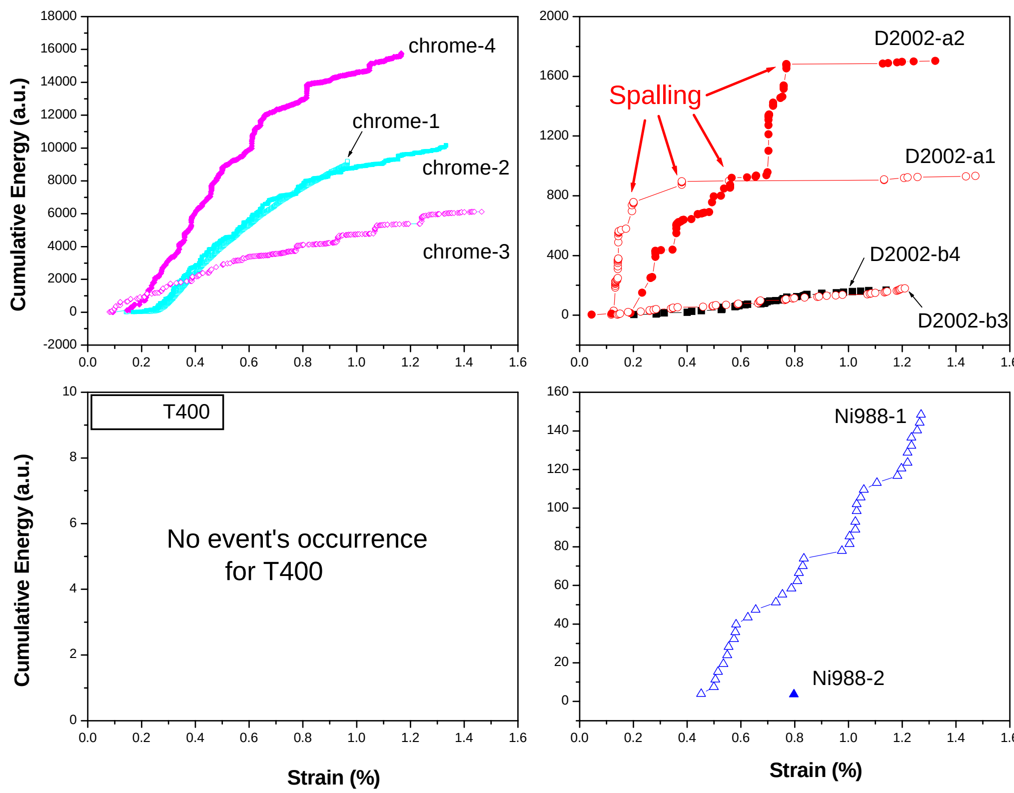



**Figure 4-21. Cumulative acoustic energy vs strain for baseline EHC and plasma spray ID coatings.**

Coatings made from electroplated chrome exhibit a large number of AE events in comparison to the other tested coatings. The number of events varies significantly from one specimen to the other (Figure 4-20). Nevertheless, despite a very different number of events (2427 vs. 747), specimens 1 and 2 coatings present a similar released cumulative energy (Table 4-5) because specimen 2 has many relatively large events. This illustrates that although a coating can develop a large number of smaller cracks, it could generate the same damage as a smaller number of larger cracks, indicative of different damage mechanisms. Thus, these two coatings represent the

same total damage by different mechanisms.

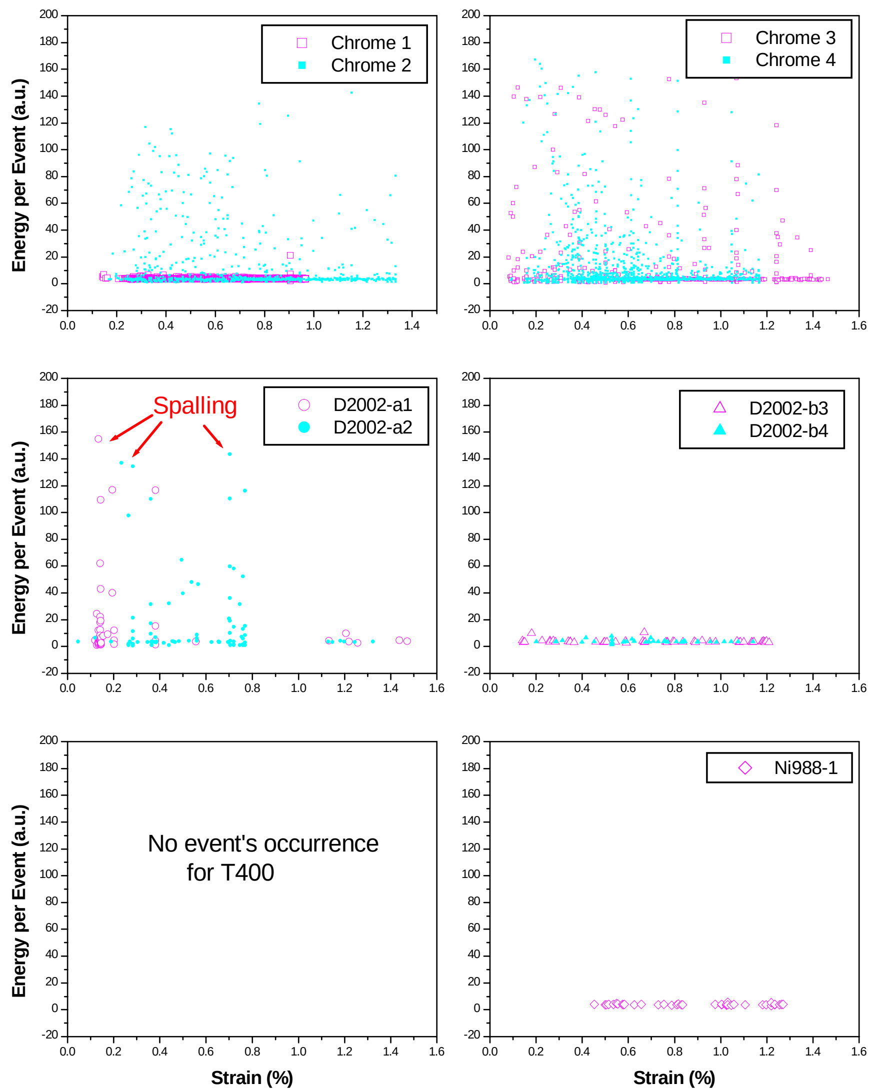



**Figure 4-22 Energy per event vs. strain.**

In contrast, specimens 3 and 4 have similar distributions of large and small events (i.e. the same damage mechanism). However, they exhibit different numbers of total AE events, resulting in a high released cumulative energy for specimen 4 than for specimen 3. While EHC specimens 1 and 2 were setup specimens, numbers 3 and 4 were production specimens, which should be identical. The AE data once more illustrate the wide variability found with chrome plate.

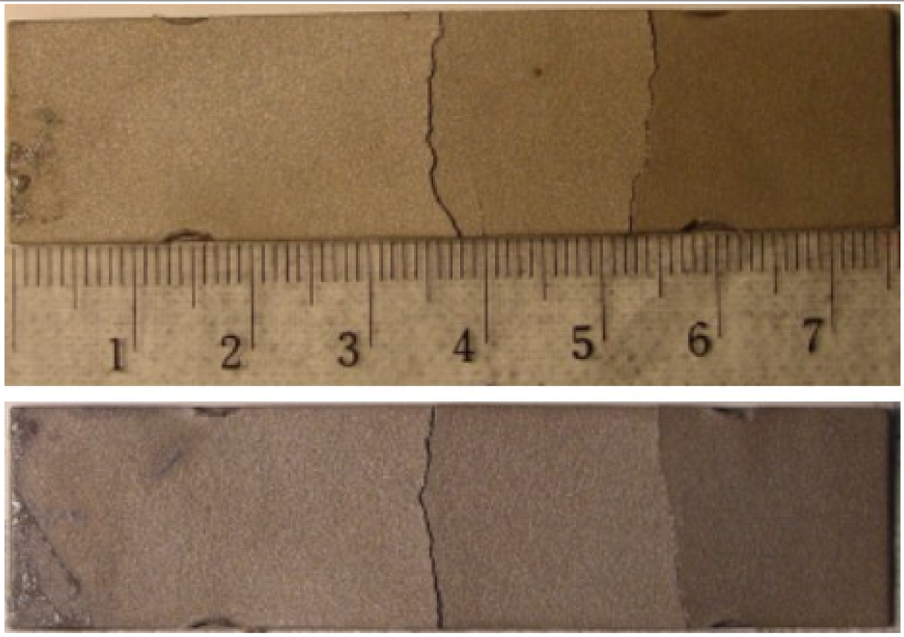



**Figure 4-23 Specimens D-2002 a1 and a2 (0.015-0.016" thick) after testing, showing cracks. Millimeter scale shown.**

# 4.6. Fatigue

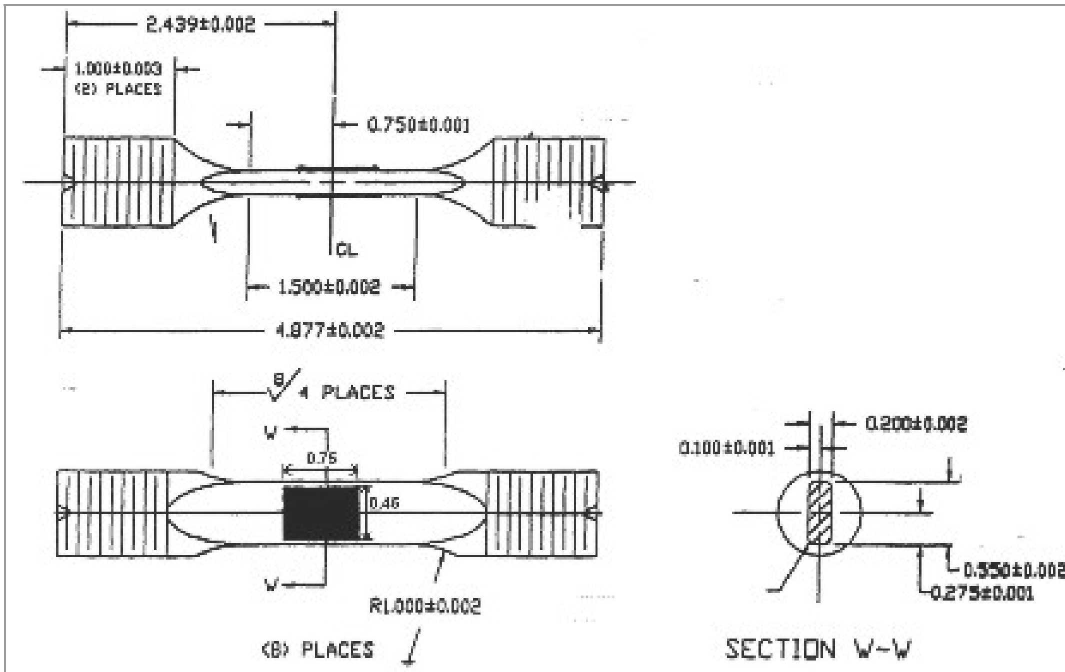



**Figure 4-24 Kb bar fatigue specimen.**

Most axial fatigue testing is done with cylindrical specimens (smooth bar or hourglass). Because there was no simple feasible method for coating this type of specimen in an ID geometry, a flat

Kb bar specimen was chosen, of a type frequently used by GE Aircraft Engines (see Figure 4-24). The coating was applied as a patch with feathered edges on both flat faces.

The specification for finishing of fatigue specimens was a 4µ" Ra surface, but the porosity of the Tribaloy 400 and the Praxair self-fluxing material proved to be too high to be able to achieve this fine a finish (see Figure 4-25, which shows the coated areas (0.75" x 0.46") on the surfaces of the fatigue specimens). It is not clear why these materials could not be finished as well as the other materials that had similar porosities, although it is often difficult to obtain a good finish on Tribaloy, even when deposited by HVOF, which gives much lower porosity.

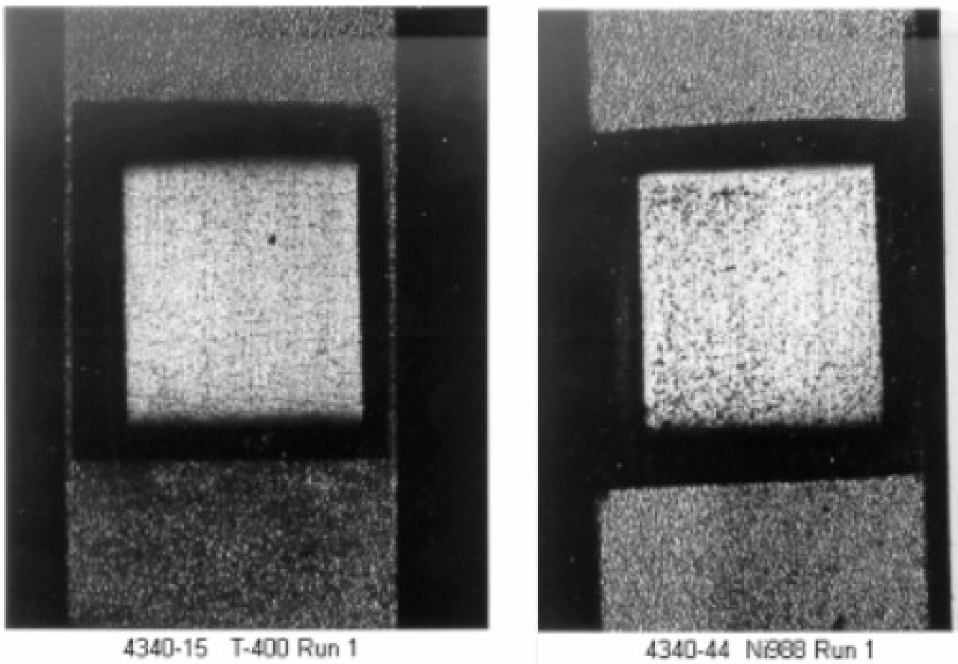



**Figure 4-25 Surfaces of Tribaloy 400 (left) and Praxair 50%WC-12Co/50% self fluxing (right) coatings on fatigue specimens.**

Each fatigue curve was generated from 15 specimens, typically 3 specimens at 5 stress levels, although stresses were chosen to obtain a full curve, with runout defined as $10^7$ cycles. Maximum stresses were 220ksi, which is just below yield, and above the maximum that would be expected for most landing gear components or any actuator components. A stress ratio of 0.025 was used (i.e. tension-tension) since compression was found to buckle this specimen design. This test configuration and method also make the data compatible with the early HCAT work [5] in which this same specimen type was used.

The results are plotted in Figure 4-26. As expected, there is a fair amount of scatter in the results. However, the curves for the plasma spray materials lie above the chrome baseline – i.e. the performance of the plasma spray coatings is better than hard chrome.

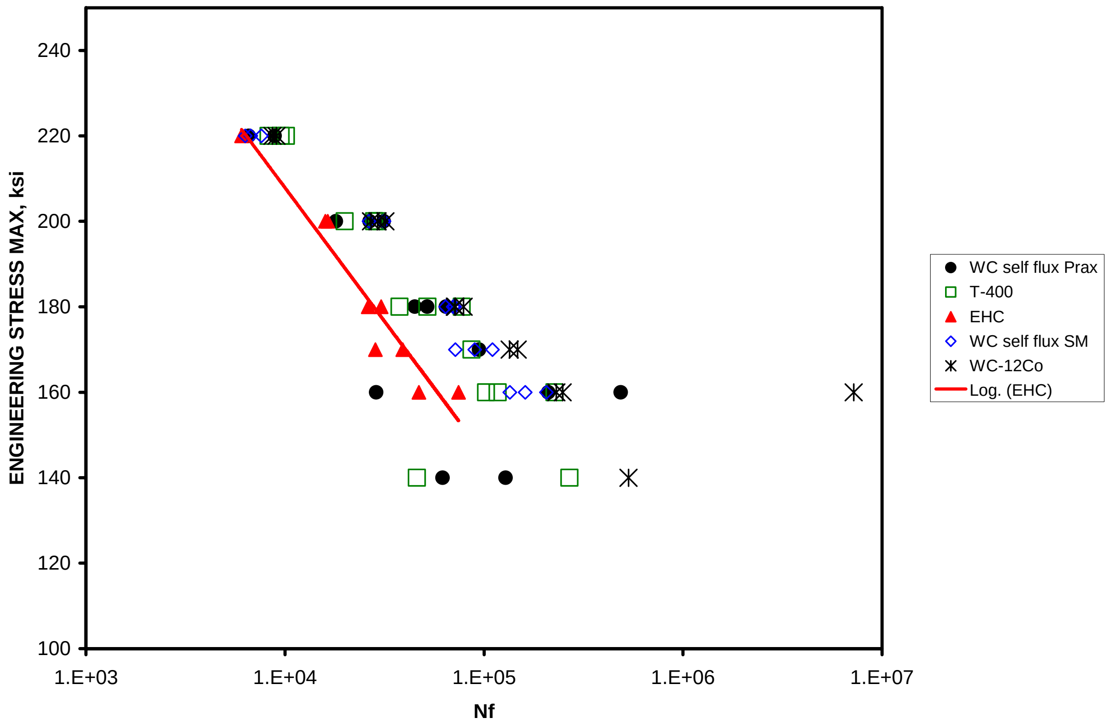



**Figure 4-26 Fatigue of ID plasma sprayed 4340. Tested in air at R=0.025.**

This was not necessarily expected since, in contrast to HVOF coatings, which are always compressive, the residual stress of plasma spray coatings is typically close to neutral and often slightly tensile. We have found that for HVOF coatings significant compressive stress is needed for optimum fatigue performance, and on the basis of this experience we would expect some debit for plasma spray.

The only result of the poor surface finish for the Tribaloy and Ni-988 self-fluxing material seems to have been additional spread in the fatigue data, but there is still a clear improvement over hard chrome.

## 4.7. Abrasive wear

### 4.7.1. Test methods

Abrasive wear was measured using the ASTM G-65 method of a rubber wheel with dry sand rubbing against the substrate (see Figure 4-27).

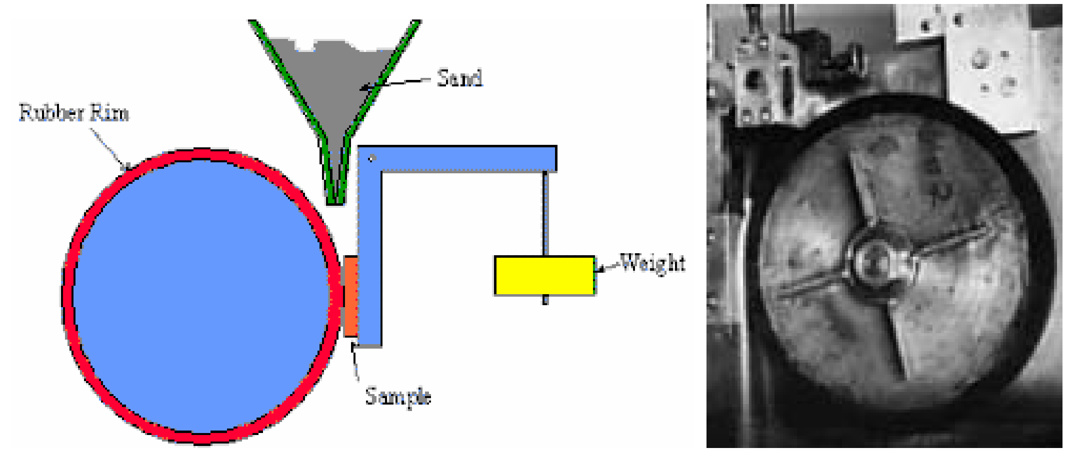



**Figure 4-27  Schematic of ASTM G65 abrasion test.**

This is a standard abrasion test, which is not directly relevant to ID coatings.  However, since it is possible for ID coatings to be scratched by debris entrained in seals it was considered worthwhile carrying out this test to evaluate how closely the abrasion resistance depends on the hardness.

### 4.7.2. Results

The results of the abrasion tests are shown in Figure 4-28.  Note that there is significant variation in the chrome plate performance.  If this variation is used to establish a performance band for the EHC, then all the plasma spray materials fall within or below the band, with the exception of the Tribaloy 400, which is much softer (see Figure 4-15).  As expected, the WC-12Co coating, which is the hardest of the plasma sprays, has significantly lower wear than the chrome average.  Data were not acquired for Ni5Al since it is not a chrome replacement coating.

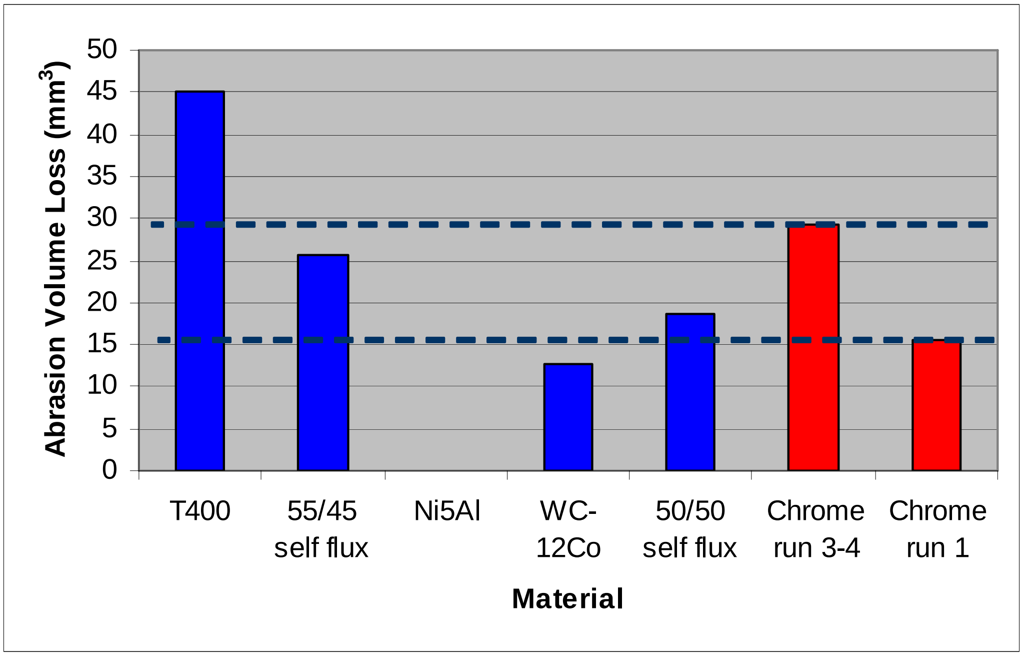



**Figure 4-28. Abrasion resistance of EHC and plasma spray coatings.**

## 4.8. Sliding wear

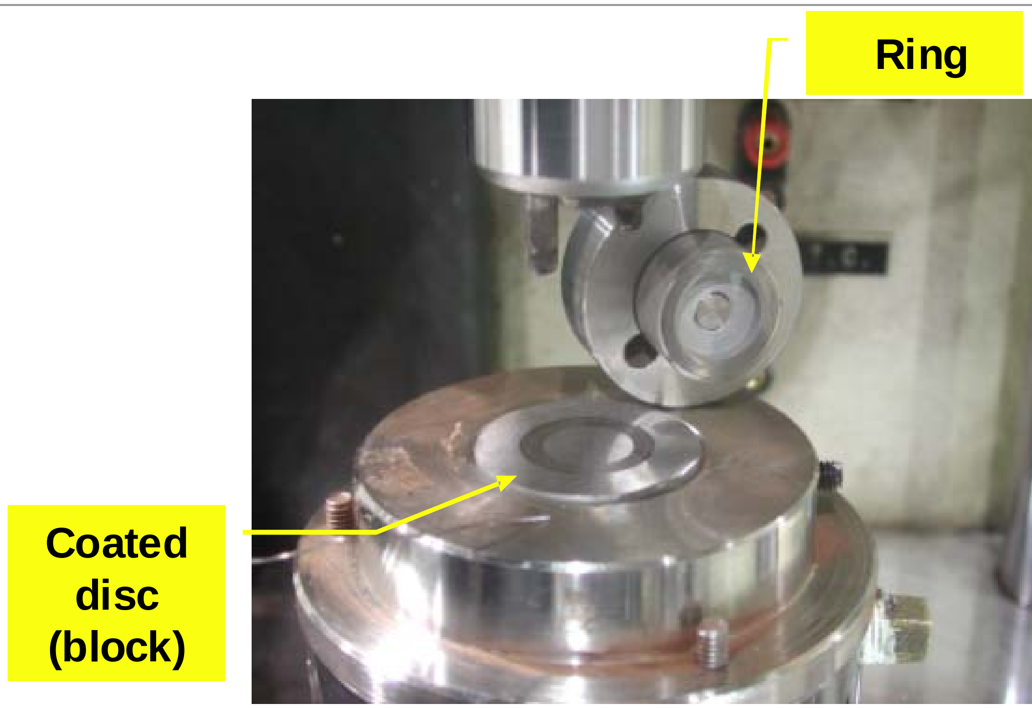



**Figure 4-29 Ring-on-block wear tester. Ring tilted to show design.**

Sliding wear was measured using a ring-on-disk tester, as shown in Figure 4-29. (In this figure

the ring has been tilted over to show the wear surface.) This test design was chosen over the more common pin-on-disc method because the forces at the wear surface are more realistic in the ring-on-disk arrangement. The disc (block) was a coated 4340 specimen and the ring (rotor) was an uncoated 52100 bearing steel.

The wear data are shown in Figure 4-30. All of the plasma spray materials show higher wear than chrome plate. However, note that in most actual components it is the wear of the total system that is most important. Sometimes one component is designed to be sacrificial, but in general the aim is to ensure good wear life for both components. Thus a component that does not itself wear but that causes excessive wear in the counterface is usually unacceptable. The hard chrome shows little wear while most of the wear is on the counterface (again, the hard chrome performance is quite variable). The plasma spray carbides behave in a similar manner, and all fall within the wear band of the chrome system. The carbides show wear in the same range as EHC. Again, the Tribaloy performs differently, with most of the wear being on the Tribaloy coating. Note that the WC-$Cr_3C_2$-NiCr, which is one of the hardest of the coatings, has quite poor wear resistance. (52100 steel, which is a standard bearing alloy, is shown for comparison.)

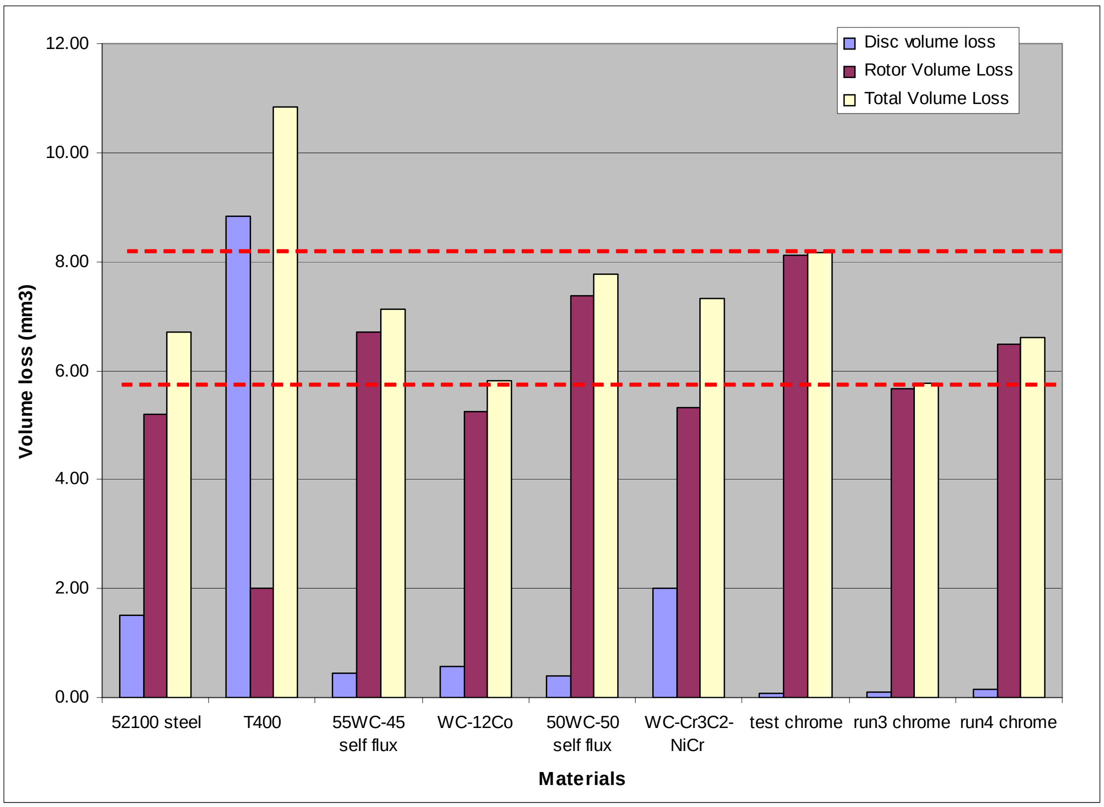



**Figure 4-30. Ring on block wear test results for EHC and plasma spray coatings.**

It is important to remember that wear tests are only indicative of general behavior. Wear is such a complex process that it can only be reliably measured on actual systems in realistic rig tests.

## 4.9. Corrosion

Corrosion data were taken on coated 4340 steel using the laboratory standard methods of linear

polarization and electrochemical impedance spectroscopy (EIS), as well as the ASTM B117 salt fog method.

The results of the electrochemical tests are shown in Figure 4-31. The corrosion currents are significantly higher for the plasma sprays than for the EHC. This is to be expected since in the plasma sprays (as with HVOF coatings) the Co dissolves in the solution, while for hard chrome it is only the substrate that dissolves through cracks in the coating. Given this basic difference in behavior it is actually quite surprising how low the corrosion currents are for the 50/50 self fluxing material (Ni-988), although it is not at all obvious why it should be so different from the 55/45 material (D-2002).

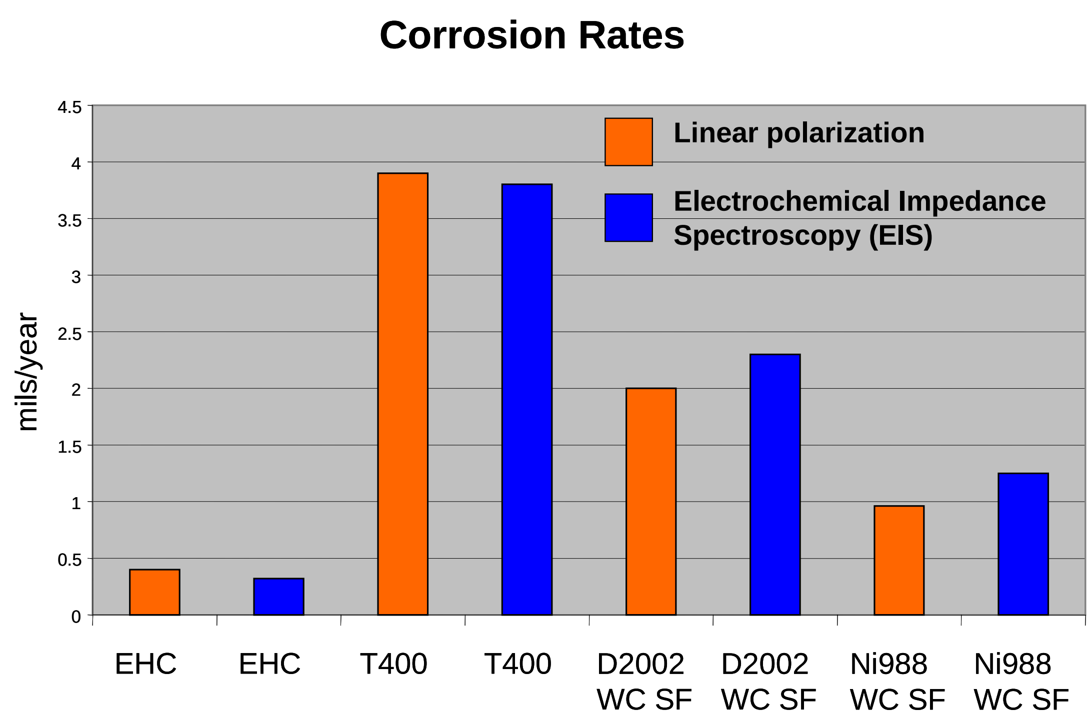



**Figure 4-31. Linear polarization and EIS corrosion data.**

Salt fog testing was carried out on standard 3"x4" plates at NRL's Key West corrosion facility. Following standard test procedure, the uncoated surfaces of the specimens were sealed with epoxy and they were tested in a rack using 3.5% NaCl salt fog. The test matrix included thick, thin, as-sprayed and ground specimens. Some specimens were sealed with a standard polymer sealer. The sealer used by Praxair was a thin wipe-on wipe-off sealer. The Sulzer Metco sealer was very thick and was peeled off prior to testing as it did not represent sealers used in hydraulics or similar applications.

**Table 4-6. B117 salt fog results after 500 hrs.**

| NRLKW Sample Designation | Manufacturer | Powder | Coating Material | Thick-ness | Finish | Sealed ? | Protection Rating (as received) | Protection Rating (after scrub) |
|---|---|---|---|---|---|---|---|---|
| HCAT #1D2 | Praxair | NI988 | WC self flux | 0.008" | As-sprayed | N | 0 | 0 |
| HCAT #1D3 | Praxair | Co-109-3 | Tribaloy 400 | 0.003" | Ground | N | 0 | 0 |
| HCAT #1D4 | Praxair | NI988 | WC self flux | 0.003" | Ground | N | 0 | 0 |
| HCAT #1D5 | Praxair | Co-109-3 | Tribaloy 400 | 0.008" | As-sprayed | N | 0 | 0 |
| HCAT #1D6 | Praxair | NI988 | WC self flux | 0.003" | Ground | Y | 6 | 4 |
| HCAT #1D7 | Praxair | Co-109-3 | Tribaloy 400 | 0.003" | Ground | Y | 2 | 0 |
| HCAT #1D10 | Sulzer-Metco | Diamalloy 2002 | WC self flux | 0.003" | Ground | Y* | 5 | 1 |
| HCAT #1D11 | Sulzer-Metco | Diamalloy 2002 | WC self flux | 0.009" | As-sprayed | N | 1 | 0 |
| HCAT #1D12 | Sulzer-Metco | Diamalloy 2002 | WC self flux | 0.003" | Ground | N | 1 | 0 |
| HCAT #1D13 | Sulzer-Metco | Diamalloy 2003 | WC-12Co | 0.003" | Ground | N | 0 | 0 |
| HCAT #1D14 | Sulzer-Metco | Diamalloy 2003 | WC-12Co | 0.009" | As-sprayed | N | 0 | 0 |
| HCAT #1D16 | Sulzer-Metco | Diamalloy 2003 | WC-12Co | 0.003" | Ground | Y* | 0 | 0 |

* Very thick sealer peeled off prior to testing.

**Table 4-7. ASTM B117 rating scheme.**

| Area Covered by Defects (% of total coating area) | Rating |
|---|---|
| 0 | 10 |
| 0 to 0.1 | 9 |
| 0.1 to 0.25 | 8 |
| 0.25 to 0.5 | 7 |
| 0.5 to 1.0 | 6 |
| 1.0 to 2.5 | 5 |
| 2.5 to 5 | 4 |
| 5 to 10 | 3 |
| 10 to 25 | 2 |
| 25 to 50 | 1 |
| >50 | 0 |

Specimens were evaluated at 250 and 500 hours using the ASTM rating system defined in Table 4-7. After 500 hours of testing they were scrubbed to remove corrosion product and break open the blisters, and re-evaluated to obtain the second protection rating shown in the right-hand column of Table 4-6.

The best results were obtained with sealed coatings, with the WC self-fluxing (Ni-988) coating having the best performance. This specimen is shown in Figure 4-32 after 0, 250 hours, and 500 hours of testing. Figure 4-33 shows the same specimen after scrubbing.

Figure 4-34 and Figure 4-35 show the second best specimen (HCAT#1D10). Note that for this specimen the initial thick seal coat applied by Sulzer Metco was peeled off before testing. Although the protection rating for this specimen was low, the damage was confined to one side of the specimen, with very little corrosion on the other side, suggesting that the material can be quite corrosion-resistant, but that this corrosion resistance is not uniform.

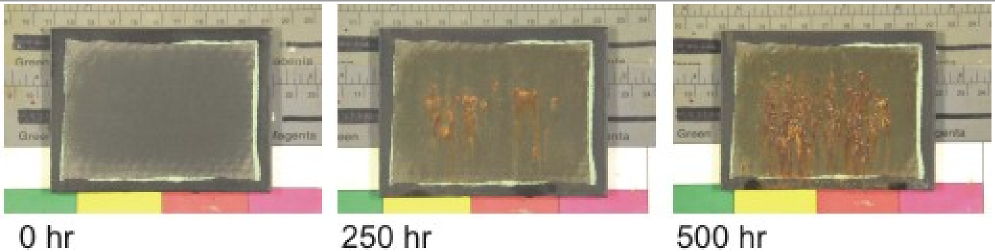



**Figure 4-32 Photographs of specimen surface of specimen HCAT#1D6 (NI988 WC self flux 0.003”) after 0, 250 and 500 hr B117 testing.**

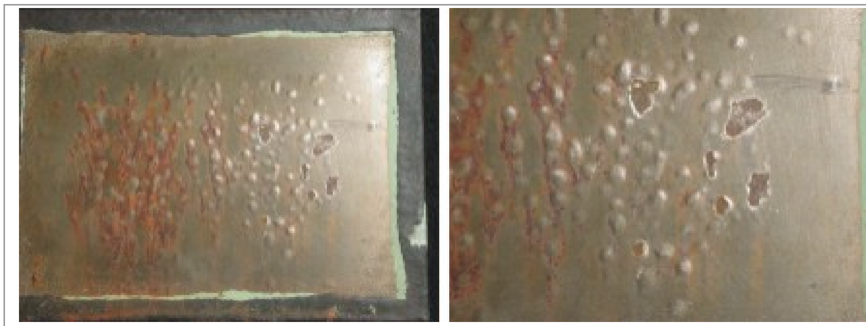


**Figure 4-33 Specimen HCAT#1D6 after 500 hrs B117. Left after scrubbing, right higher magnification.**

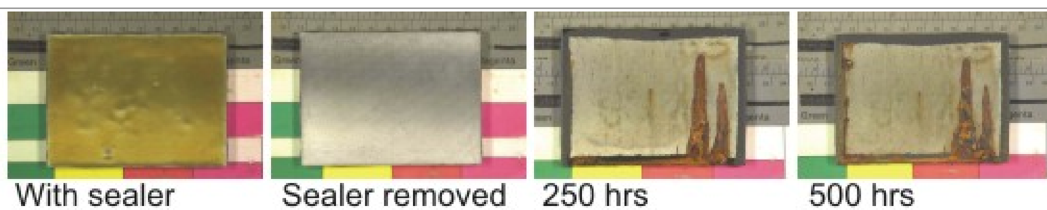



**Figure 4-34 Photographs of specimen surface of specimen HCAT#1D10 (D2002 WC self flux 0.003” with original sealer, and sealer removed after 0, 250 and 500 hr B117 testing.**

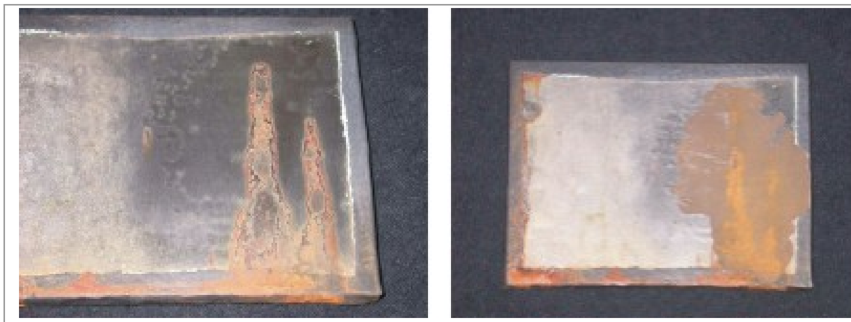
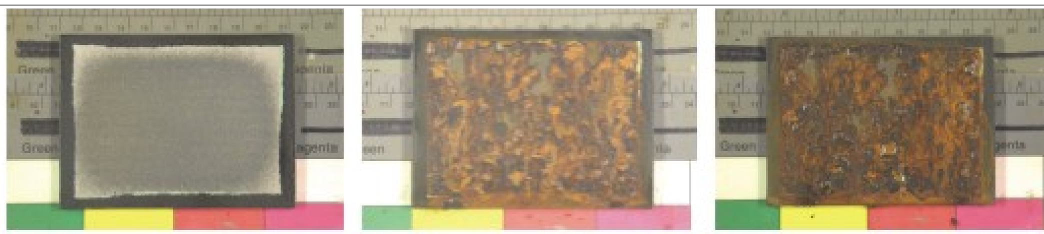


**Figure 4-35 Specimen HCAT#D10 after 500 hrs B117. Left after scrubbing. Right after scraping away loose coating.**



0 hr 250 hr 500 hr

**Figure 4-37 Photographs of specimen surface of specimen HCAT#1D3 (unsealed Co-109-3 Tribaloy 400 0.003”) after 0, 250 and 500 hr B117 testing.**

0 hr 250 hr 500 hr

**Figure 4-36 Photographs of specimen surface of specimen HCAT#1D7 (sealed Co-109-3 Tribaloy 400 0.003”) after 0, 250 and 500 hr B117 testing.**

A more common situation is shown in Figure 4-37. This coating was unsealed Tribaloy 400. Corrosion was uniform across the surface, with corrosion product bleeding out through the porosity in the coating. However, sealing did provide some protection, as shown in Figure 4-36 for the equivalent sealed coating. Scrubbing the surface showed heavy corrosion, and scraping removed almost all the coating (Figure 4-38).

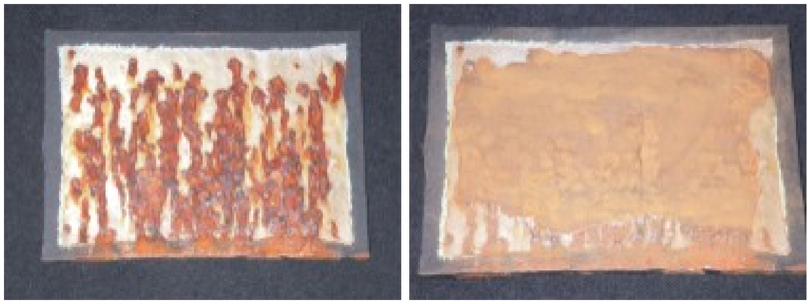


**Figure 4-38 Photographs of specimen surface of specimen HCAT#1D7 (sealed Co-109-3 Tribaloy 400 0.003") after 500 hr B117. Left, after scrubbing; right, after scraping away loose coating.**

Clearly, these plasma spray coatings do not perform as well as HVOF coatings, which is not surprising due to their much higher porosity. While sealing does provide some protection, it is not of any great value for corrosion protection.

It was therefore concluded that these materials are not suitable for use in situations where corrosion is likely to be a serious issue. They should perform well, however, in situations where they are protected, such as hydraulic actuators and dampers, where they are usually immersed in hydraulic fluid.

# 5. Equipment test and development

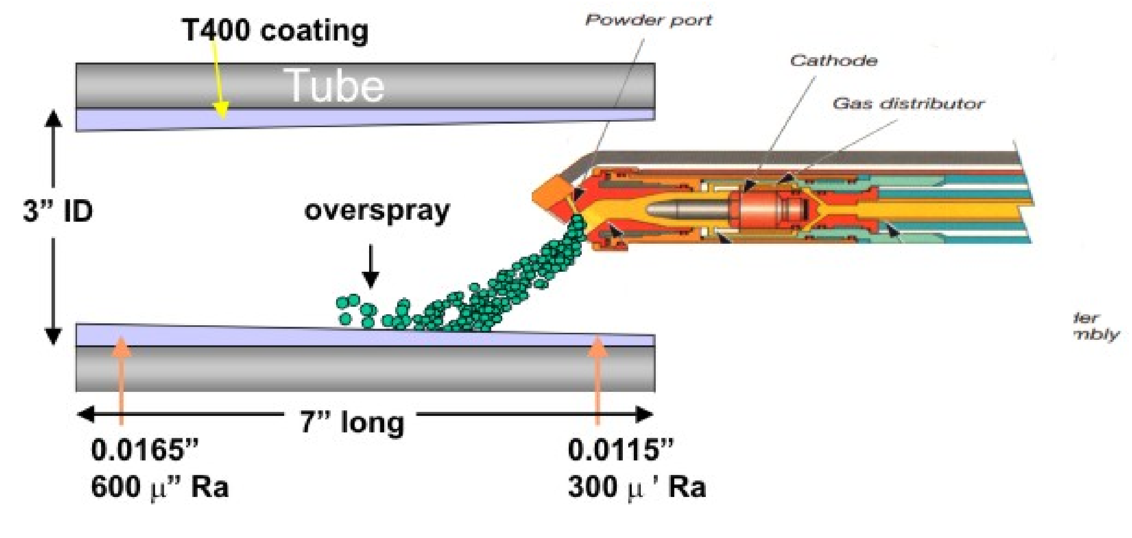



**Figure 5-1 Schematic of T400 coating inside 3" ID tube. Result of 15 complete in-out cycles (30 passes).**

It was found early in the program that, absent any air jets to remove the overspray powder, the coating became thicker deeper into the tube through incorporation of unmelted overspray as illustrated in Figure 5-1. Considerable effort was put into developing methods for measuring and removing this overspray. In addition to removing the overspray, air jets also help to remove heat from the system.

## 5.1. Overspray removal

When a thermal spray gun is used for OD spray the overspray (powder that does not adhere to the substrate) is easily swept away by the cooling air jets and the plasma gas itself. However, in an ID this powder can easily be trapped in the spray region and can settle on the surface, becoming incorporated into the coatings as they are sprayed. This was clearly demonstrated at Praxair, where thicker coatings were produced deep within the ID tube than near the outside. Praxair installed additional gas feeds to flush the overspray away from the coating area, but the initial arrangement was far from ideal.

In order to optimize overspray removal NRC designed and built an optical overspray measurement system, which they call the Fumespector (see Figure 5-2). It can be rotated about the gun to map out the areas in front and behind the spray region as the tube

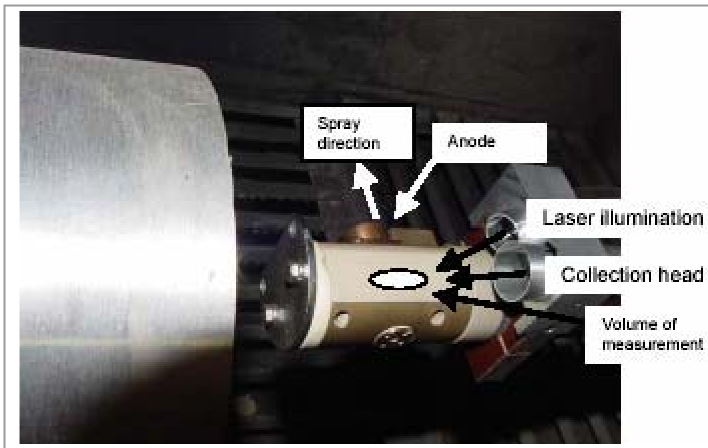



**Figure 5-2. Overspray sensor head (Fumespector) attached to F-100 spray gun (NRC).**

rotates about the gun and the gun moves in and out. A laser beam illuminates an area while an optical fiber collects light scattered from particles on an intersecting line. The intersection of laser and fiber collector area defines the volume being analyzed, which is about 1x1x10mm. The initial device was made for use in a 6" diameter tube for proof-of-principle testing. The device was then rebuilt on a smaller scale to fit into a 3" ID.

The device is clearly sensitive to the amount of spray powder and to spray geometry, as Figure 5-3 shows. The signal strength is roughly linear with spray powder volume. With both open-end and closed-end tubes, an air jet can be used to reduce the particle count. However, the particle count in the closed-end tube is still an order of magnitude higher than in the open-end geometry.

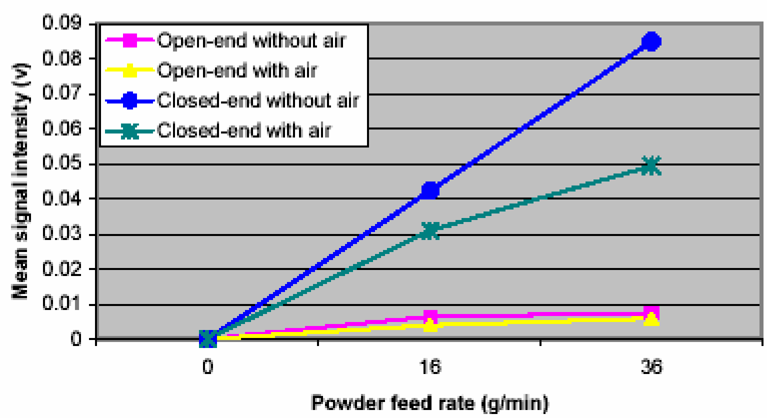



**Figure 5-3. Optical signal for $Cr_2O_3$ powder spray with Praxair 2700 gun, using air sprayed into the cylinder.**

Figure 5-4 shows the optical signals (i.e. the dust densities) for two geometries. Figure 5-4A is the situation for a geometry with a high rate gun (the F100) and gas flow across the cylinder. Figure 5-4B is the situation for the smaller SG-2700 gun with gas flowing through the cylinder. There is a two order of magnitude difference, due primarily to the gas flow direction, which only sweeps out the powder effectively in geometry B.

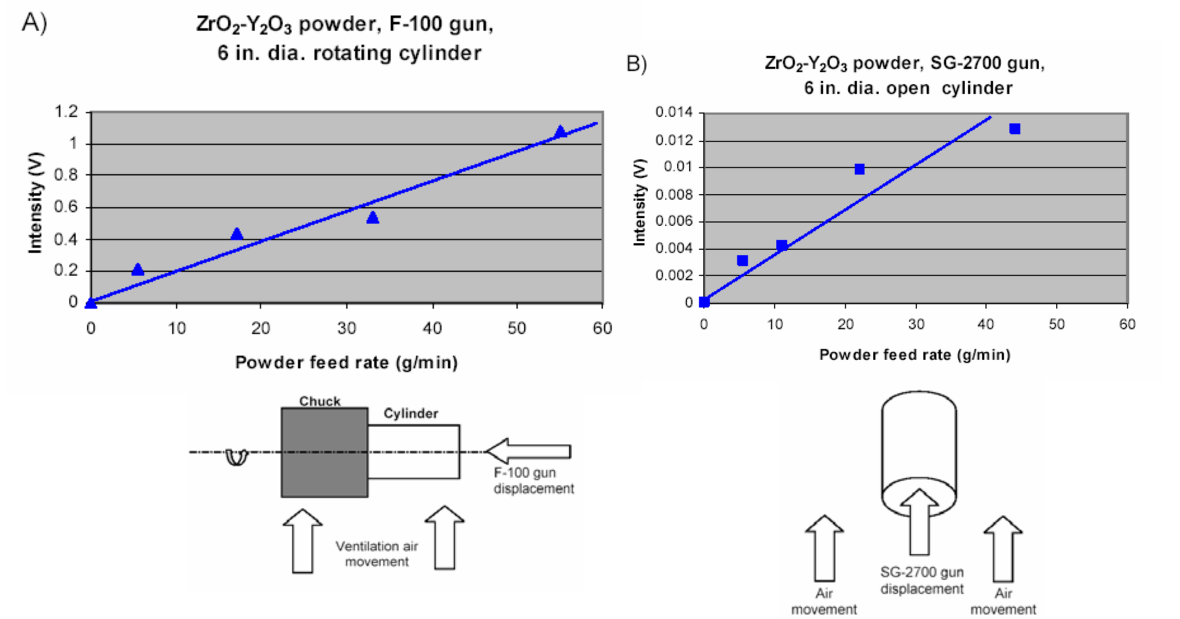



**Figure 5-4. Optical signals for two different gas feed geometries. A) F100 gun with gas flow across outside of rotating cylinder; B) SG-2700 gun with gas flow through stationary cylinder. Note intensity scales.**

The Fumespector was set up to evaluate several arrangements for the sparging gas, which is designed to blow the overspray dust away from the coating zone. These are shown in Figure 5-5.

In the top picture of Figure 5-5 the sparging gas jet is aimed at the ID wall, in the direction of the plasma spray; in the center picture the gas jet is aimed toward the end of the cylinder, beyond the plasma spray; in the bottom picture a series of jets in a line are aimed at the wall to clear a wide area. In any of these geometries the gas jet may be either side of the plasma jet (i.e. in front of or behind the plasma jet as the wall passes in front of it). The optical head could be moved around the gun to evaluate the overspray at different areas.

Figure 5-6 shows how the optical signal varies with plasma gun position in the tube. Outside the tube (left and right side) the signal is very low because there is little or no scattering. As the gun enters the tube the signal rises to an approximately constant value. At the bottom of the tube (time 5.5 to 7) the signal is high primarily because of reflection from the end of the tube. This masks the signal due to overspray, which would be expected to be higher in this region.

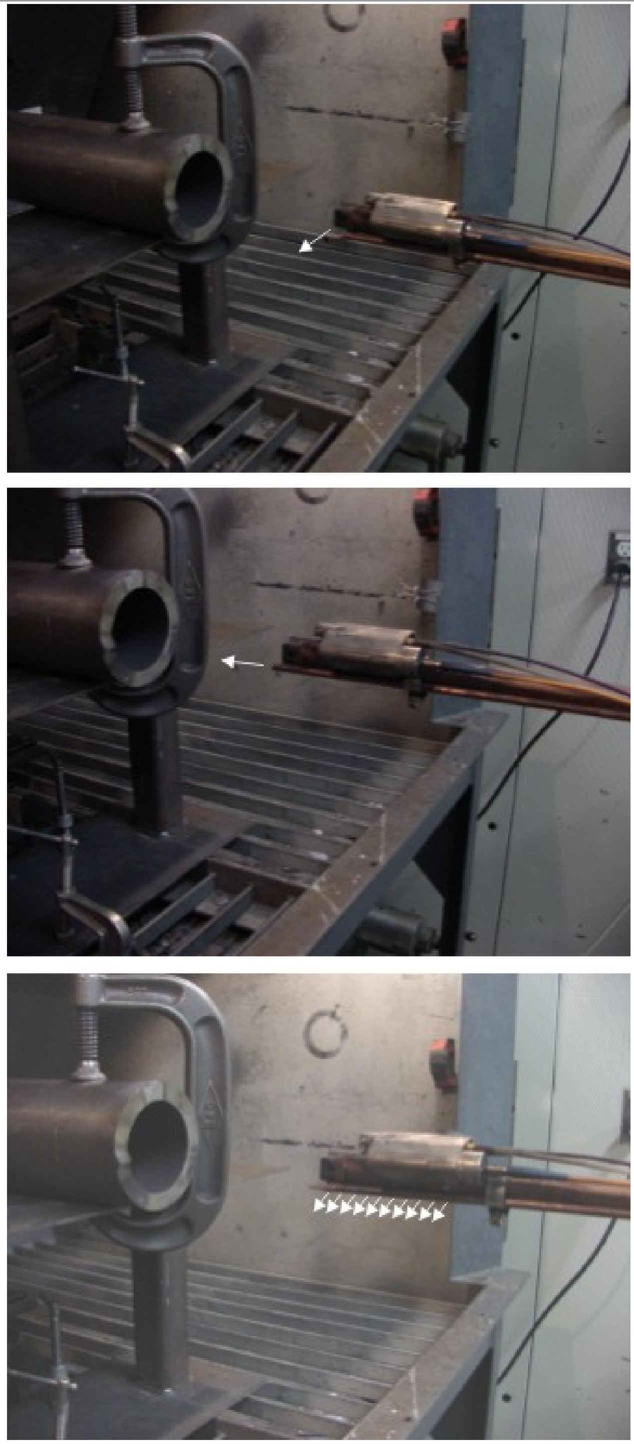


**Figure 5-5 Sparging gas arrangements for ID plasma spray. Top – side on; middle – end on; bottom – line.**

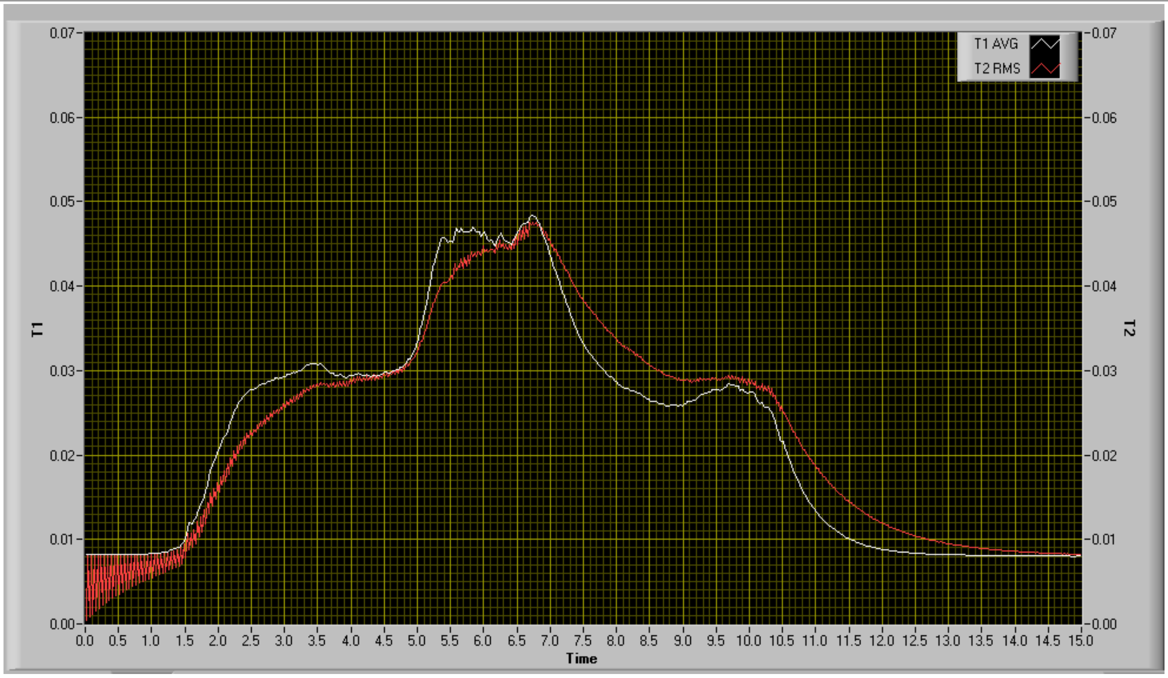



**Figure 5-6 Optical signal as the spray gun is moved into and out of a blind tube.**

**Table 5-1. Optical signals from Fumespector for different sparging gas arrangements.**

| Configuration | Mean signal (mV) | RMS (mV) |
|---|---|---|
| Multiple line (right of spray) | 1781 | 22.3 |
| Multiple line (left of spray) | 2098 | 26.2 |
| Side-on (right of spray) | 2980 | 37.3 |
| Side-on (left of spray) | 3013 | 37.7 |
| End-on (right of spray) | 2648 | 33.1 |
| End-on (left of spray) | 1729 | 21.6 |

Work was done to evaluate the optimal arrangement of sparging gas flow direction. Data for spraying within a stationary tube are given in Table 5-1. The level of overspray varies by about a factor of two, with no clear logic to the geometry. Testing was done to understand the best arrangement and to apply it to real spray conditions. Working with NRC, Praxair was able to improve overspray removal by adding two air spray jets to their standard 2700 ID gun (Figure 5-7).

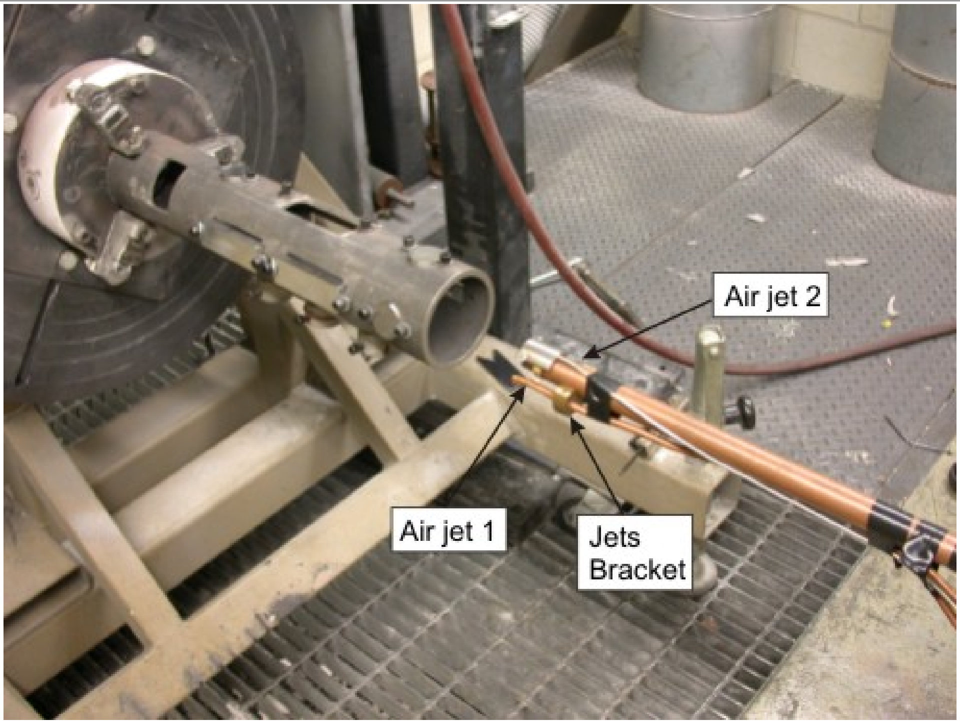



**Figure 5-7 Air jet installation on Praxair 2700 gun.**

However, it is important to note that if an existing gun is equipped with additional jets, one must re-optimize the deposition conditions. This is because the presence of the air jets within the cavity not only blows away the overspray but also changes the deposition conditions at the point of impact. Depositions were performed in which reconfiguring the jets to reduce the overspray signal was found to impair the performance of the coating for this reason.

## 5.2. F300 Miniature spray gun performance

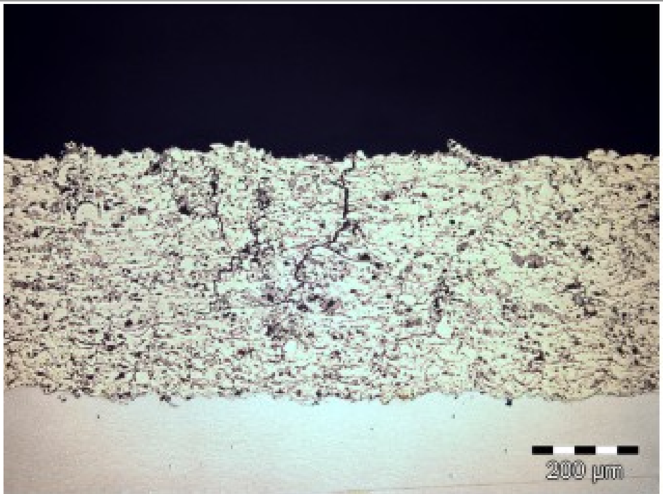
During the course of the project Sulzer Metco put a new miniature ID gun, the F-300, onto the market. This new gun is similar in external design to the F-210 used for the bulk of this work (see Figure 5-8). However, it can be used in smaller diameters.

In tests of this gun at Sulzer Metco it has successfully sprayed acceptable quality coatings into IDs down to 1.6”.

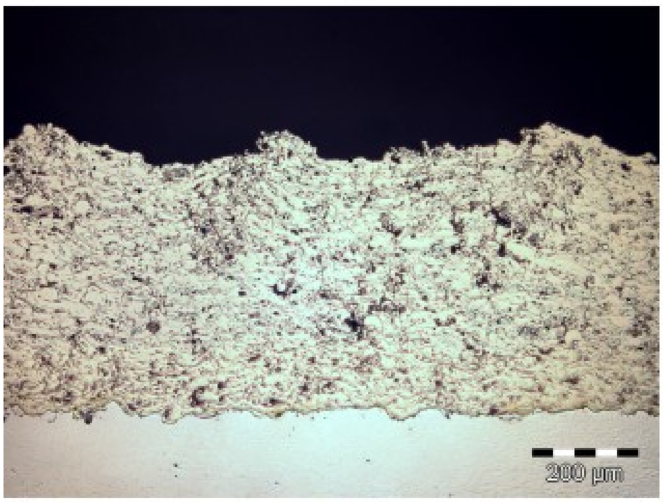
Figure 5-9 shows the microstructure of a 55WC/45 self fluxing coating deposited with this gun at a standoff of 1.7”. Note that the hardness is lower than with the F210 gun (533 HV compared with 673 HV). Figure 5-10 shows similar data for a nanophase WC-Co coating. The microhardness of this material is 612 HV compared with 827 HV for standard WC-12Co using the F-210 gun. This reduction in hardness is indicative of carbide dissolution, which is common when spraying nanophase materials (which is why the use of nanophase carbides for standard ID guns was abandoned early in the project). (See Appendix 6 for a full discussion of nanospray.)

**Figure 5-8   F-300 ID spray gun.**

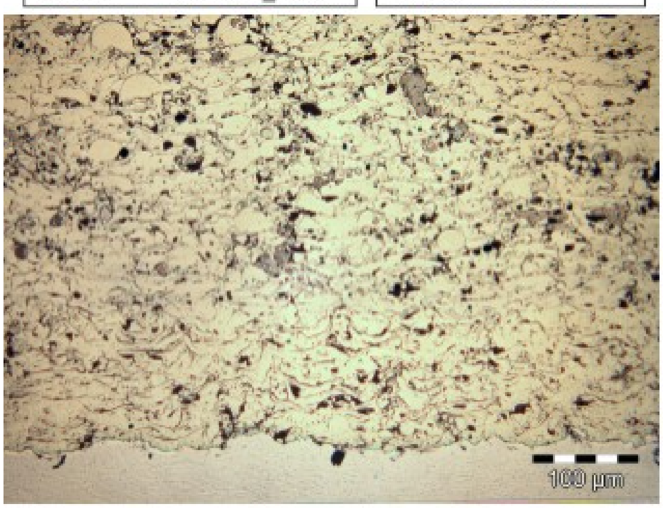
Clearly there is a need to optimize these coatings with this gun (which is being done commercially by Sulzer Metco), but the results are encouraging, showing that it is possible to spray reasonable quality coatings within an ID of 1.6”.  This makes it possible to use plasma spray to coat the IDs of many flight surface actuators, not just the utility actuators and landing gear cylinders accessible to standard ID guns.




| | | | |
|---|---|---|---|
| Record | 21500- | Etchan | None |




| | | | |
|---|---|---|---|
| Record | 21500-2_100b | Etchan | None |




| | | | |
|---|---|---|---|
| Record | 21500-2_200 | Etchan | None |

| **Project #:** | f |
|---|---|
| Customer: | |
| Project | M. Nestler |
| Submitted | J. Leach |
| Metallograp | Manfred Stapgens |
| Job #: | 19384 |
| Material [Top | Self-flux |
| Material [Bond | Ni-base |
| Spray | F-300 mod , 1.7" ID |
| Spray Run #: | 962503 -1 |
| Mount #: | 21500 -2 |

| | |
|---|---|
| Roughness | N/D |
| Macrohardness: | HR15N |
| Avg. + | 78.9 ± 1.5 |
| min - | (77.0 – 81.6) |

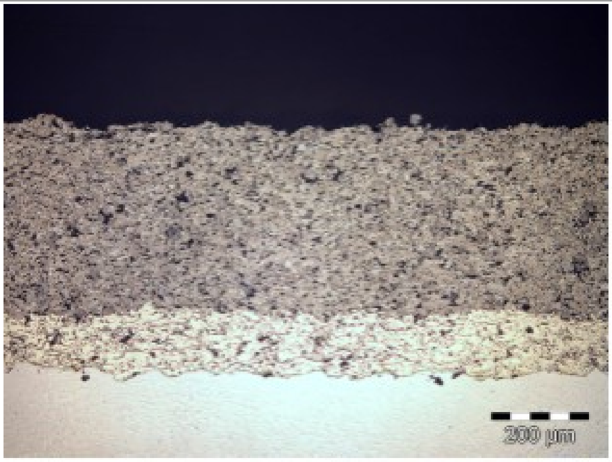
| **Material [Bond** | **Ni-base** |
|---|---|
| Interface: | clean, good bond ing |
| **Cracks-** | none |
| Porosity [%]: | N/D |
| Oxide [%]: | N/d |
| Thickness | 0.004 – 0.005 |
| Microhardness: | N/D |
| Avg. + | |
| STD: min - | |

| **Material [Top** | **Self-flux** |
|---|---|
| Interface: | clean, good bonding |
| **Cracks-** | yes |
| Porosity [%]: | 4.8 ± 0.8 (4.1 – 5.7) |
| Oxides [%]: | < 1 |
| Thickness [inch]: | 0.014 – 0.015 |
| Microhardness: | HV0.3 |
| Avg. + | 533 ± 140 |
| STD: min - | (226 – 656) |

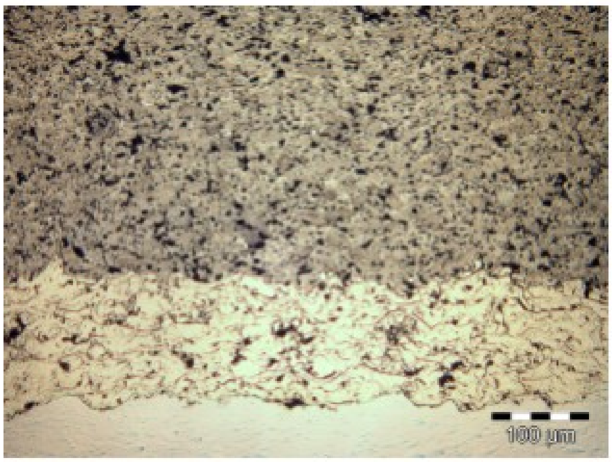
Comment:

Unmelts: Yes

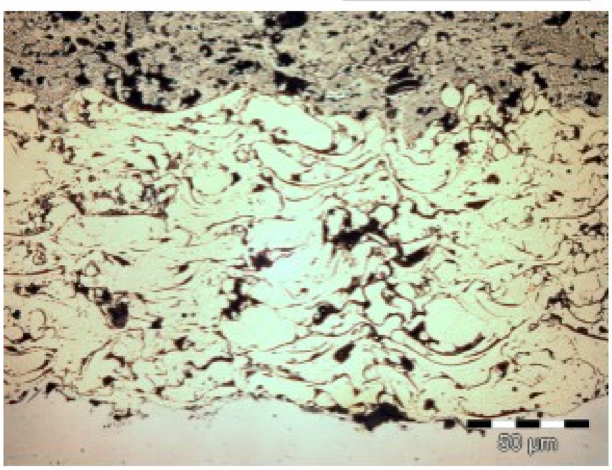
**Figure 5-9 Summary of microstructures of 55WC/45 self-fluxing plasma spray coating deposited by F-300 gun (Sulzer Metco). Top – cracked region, Center – uncracked region, Bottom – higher magnification.**




| | | | |
|---|---|---|---|
| Record Name: | 21501 -1_100 | Etchant: | None |




| | | | |
|---|---|---|---|
| Record Name: | 21501 -1_200 | Etchant: | None |




| | | | |
|---|---|---|---|
| Record Name: | 21501 1_500a | Etchant: | None |

| | |
|---|---|
| **Project #:** | **06103** |
| Customer: | |
| Project Manager: | M. Nestler |
| Submitted By: | J. Leach |
| Metallographer: | Manfred Stapgens |
| Job #: | 19384 |
| Material [Top Coat]: | AE8155 |
| Material [Bond Coat]: | Ni-base |
| Spray Process: | ID gun; 1.7" ID |
| Spray Run #: | 962503 -2 |
| Mount #: | 21501 -1 |

| | |
|---|---|
| Roughness [uinch]: | N/D |
| Macrohardness: | HR15N |
| Avg. + STD: | 77.1 ± 1.2 |
| min - max: | (75.3 – 78.9) |

| | |
|---|---|
| **Material [Bond Coat]:** | **Ni-base** |
| Interface: | clean, good bond ing |
| Cracks -Delaminations: | none |
| Porosity [%]: | N/D |
| Oxide [%]: | N/D |
| Thickness [inch]: | 0.005 – 0.006 |
| Microhardness: | HV0.3 |
| Avg. + STD: | 612 ± 107 |
| min - max: | (476 – 833) |

| | |
|---|---|
| **Material [Top Coat]:** | **WC -nano** |
| Interface: | clean, good bonding |
| Cracks -Delaminations: | |
| Porosity [%]: | 8.7 ± 0.4 (8 .2 – 9.2) |
| Oxides [%]: | < 1 |
| Thickness [inch]: | 0.014 – 0.015 |
| Microhardness: | HV0.3 |
| Avg. + STD: | 612 ± 107 |
| min - max: | (476 – 833) |

Comment:

Unmelts: Yes

**Figure 5-10 Summary of microstructures of nanophase WC-Co plasma spray coating deposited by F-300 gun (Sulzer Metco). Three different magnifications. (Light coating is Ni-based bond coat.)**

This page intentionally left blank.

# 6. ID Coating Demonstration

All of the test specimens themselves demonstrate ID coating capability since they were all coated in an ID geometry (Figure 4-1). In addition test spray coatings were made on the IDs of 3” cylinders and a 3” ID landing gear component.

Figure 6-1 shows a 3” ID steel cylinder coated with WC self fluxing material (NI-988) and used to test different finishing methods.

**Figure 6-1 3" ID cylinder sprayed with WC self fluxing coating (Ni-988) and ground at end to 12-16μ” Ra.**

Silicon carbide, aluminum oxide and diamond grinding wheels were tested for the finishing trials. It was determined by the wear of the wheel and the surface finish quality that the coating is best finished by using the diamond wheel, with which a 12-16 micro-inch Ra was achieved merely by diamond wheel grinding without superfinishing. For hydraulic cylinder IDs it may, however, be necessary to superfinish to a 4μ” Ra to achieve the best surface profile and minimize seal wear.

This page intentionally left blank.

# 7. Costs and Benefits

Instead of a simple Cost-Benefit Analysis (CBA) a full Implementation Assessment was carried out, which included a CBA in addition to an analysis of production readiness and risk. The full analysis is provided in Appendix 3 in the form of a linked document. The following is a summary of the assessment.

This report assesses the implementation of plasma spray for replacement of EHC plate for overhaul of internal diameters of aircraft components at NADEP Jacksonville. Technical assessment is based upon the results of SERDP Project # PP-1151 and commercial and field experience with the technology. Cost assessment is based on data obtained in prior cost benefit analyses by NADEP Jacksonville, updated by a field visit, combined with data from a Navy/Industry task force that analyzed the impact of a new OSHA PEL.

Plasma spray is a mature thermal spray technology that is already used at NADEP JAX for engine overhaul. ID plasma spray complements HVOF by coating internal (non-line-of-sight) areas that are inaccessible to HVOF. The primary applications are IDs of landing gear outer cylinders and hydraulic actuator outer cylinders. The probability of successful qualification for these applications is high. The technology is limited to IDs above 2.5” for the two primary plasma spray guns tested (the Praxair 2700 and Sulzer Metco F210), although the new Sulzer Metco F300 gun has been demonstrated to work down to 1.6” ID. The larger F100 gun can coat IDs down to 4”, which encompasses >90% of all ID coated components overhauled at JAX.

Technically, ID plasma spray is not as mature as OD plasma spray. Equipment, spray methods and materials are fully commercial, while the specific spray method and material performance for IDs are now at a TRL 4 level, meaning that they are ready for validation and qualification. Plasma spray can coat IDs with the same coating materials with which HVOF can coat ODs. However, the performance of the ID material is somewhat below that of HVOF. It has lower hardness and wear resistance, lower adhesion strength and more porosity. However, the performance of ID plasma spray WC-Co is at least as good as, and probably somewhat better than EHC, with a likelihood of improved wear life and hence reduced repair frequency.

A standard Cost-Benefit Analysis using the C-MAT model shows that the cost of ID plasma spray using the F100 gun is approximately equal to the current cost of chrome plating. Given the cost of implementation (capital, qualification and other adoption costs) this would make the technology not cost-effective unless field testing proves the technology to have better wear resistance. However, OSHA’s proposed new PEL for $Cr^{6+}$ is 1 $\mu g\ m^{-3}$, which is a factor of 50 lower than the existing PEL. Should this level be adopted after the comment period, it is estimated by a Navy/Industry task force that the cost of chrome plating will double for the types of operations carried out at JAX. This would make the plasma spray alternative cost effective. For a complete changeover from EHC to plasma spray over 10 years, a PEL close to 1 $\mu g\ m^{-1}$, and a twofold wear life improvement, it is estimated that the Net Present Value (NPV) would be $2 million, with an Internal Rate of Return (IRR) of 14%, a Return on Investment (ROI) of 47%, and a Payback Period of 8 years.

However, this type of narrowly-focused Cost-Benefit Analysis measures only the cost and benefit to the depot itself, not to DoD as a whole. The true value to DoD of adopting ID Plasma Spray at JAX and other depots is not the limited payback calculated from in the standard manner, but is seen in two more important ways:

1. **ID Plasma Spray complements HVOF, making it possible to entirely eliminate chrome plating from DoD operations.**

2. **The turnaround time for plasma spray operations is a few hours rather than the several days needed for EHC and all the required heat treatments. The result of this, together with other time-saving measures, is faster weapons turnaround to the fleet, and a higher number of combat-ready aircraft for war operations.**

Figure 7-1 shows how the Net Present Value (NPV) for replacing ID EHC with plasma spray at NAEDP JAX changes as a function of the number of years over which the calculation is made. This is for a gradual changeover from EHC to plasma spray and assumes that the OSHA PEL will be set at 1 $\mu gm^{-3}$ and that the plasma spray does provide twice the wear life of EHC as suggested by the abrasive wear data for WC-12Co.

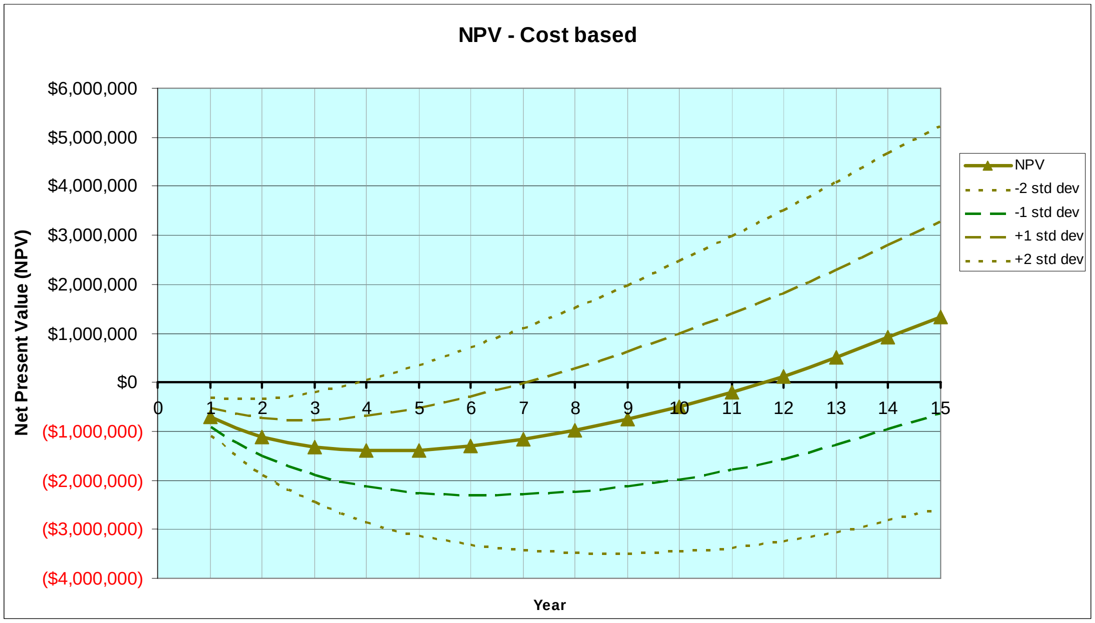



**Figure 7-1. NPV as a function of years over which it is taken, for F100 gun with OSHA PEL of 1$\mu gm^{-3}$ and improved wear performance. Assumes 10 year changeover.**

The financial return data are summarized in Table 7-1 for a 15 year period. Note that, as is common for these types of calculations, the variance in the outcome from the uncertainties in the data gives a very wide range of possible outcomes. However, under most conditions the payback is positive.

The final OSHA $Cr^{6+}$ PEL, its effect on chrome plating costs at NADEP JAX, and the performance of plasma spray on actual components are all factors that have considerable uncertainty. A calculation was made of the probability distribution for different outcomes based on a 30% probability of improved performance and a 50% probability of the new PEL doubling the cost of EHC at the depots. The result is shown in Figure 7-2.

**Table 7-1. 15-year financial results for F100 gun with OSHA PEL of 1$\mu gm^{-3}$ and improved wear performance. Assumes 10 year changeover.**

| | -2 sigma | Value | +2 sigma |
|---|---|---|---|
| NPV | ($2,588,124) | $1,321,544 | $5,231,211 |
| IRR | | 9% | 26% |
| ROI | 24% | 42% | 61% |
| Payback period (cumulative cost = 0) | >15 years | 10.5 | 3.7 |

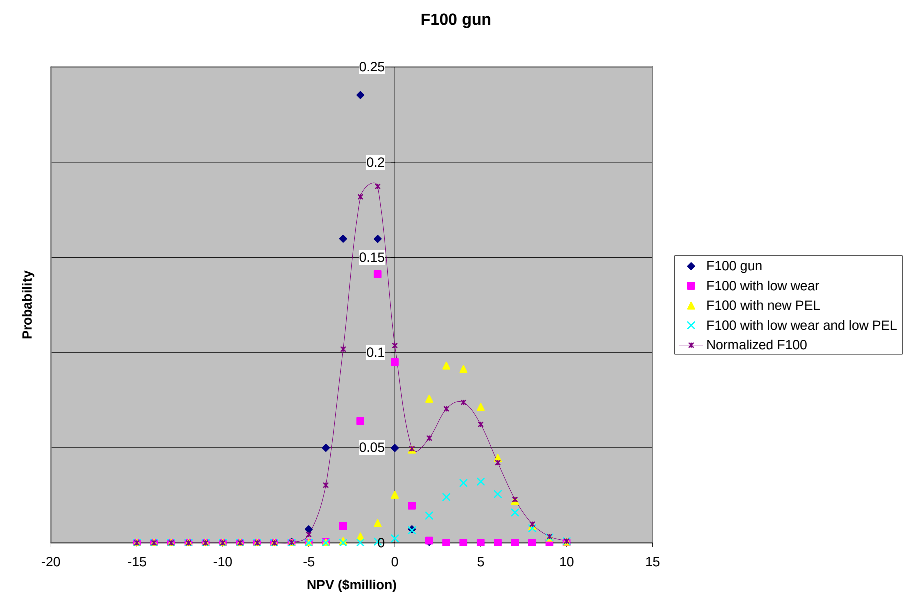



**Figure 7-2. Probability distribution for15-year NPV, assuming use of the larger F100 or similar plasma gun.**

The total probabilities of a financial loss or a profit is approximately equal (as determined from the areas under the curve in the negative and positive NPV space). This clearly does not represent a strong financial driver for replacing ID EHC with plasma spray. However, as noted above, the faster turnaround, which contributes to better war fighting capability, is a stronger driver than cost for making the change.

This page intentionally left blank.

# 8. Implementation

During a visit to NADEP Jacksonville to acquire cost assessment data the process engineer, John Lamkin, said that they would like to replace ID chrome with plasma spray primarily as a means of reducing in-process time. When using EHC a typical plating run is 24 hours, followed by a 23 hour hydrogen bake. Use of HVOF or plasma spray reduces coating time to an hour or two and eliminates the hydrogen bake. NADEP JAX has now implemented HVOF for ID coating of some items whose internal surfaces are accessible using an external HVOF gun.


**Figure 8-1 P-3 landing gear inner cylinder after Lockheed-Martin rig test (HVOF coating stripped from OD – ID usually chrome plated).**

However, this is not an approach that can be used for deeper IDs such as the P3 landing gear, which is an important part of the depot work load. Any of the ID plasma spray guns evaluated in this project could be used to plasma spray within this component, which is 48” long and 6” ID, provided they were supplied with a long enough extension to reach into the bottom of the component. (Such a long extension is not supplied for the standard gun.) Figure 8-1 shows one of these inner cylinders, which had been HVOF sprayed with WC-Co on the OD, successfully rig tested at Lockheed-Martin and then stripped to examine for substrate cracks.

Recently, Boeing has been testing ID plasma spray coatings to replace chrome plating on a commercial landing gear uplock cylinder. The ID EHC had been causing embrittlement problems, which the ID plasma spray avoids. Information from this SERDP program has been communicated to Boeing and the coating has been demonstrated, but as of the time of writing it has not yet been tested.

The new commercial Airbus 380 is also intended to be a "green" aircraft. ID plasma spray has now been specified for at least some of the hydraulics on this system. As a result of what was learned in this program, the project team was able to assist one of the vendors, who is also a vendor for the JSF, where various thermal spray coatings are also likely to be specified.

ID plasma spray has now been successfully tested and qualified for helicopter blade dampers on CH-53 and H-60 helicopters (see Figure 8-2). The cylinder ID coating is T400.

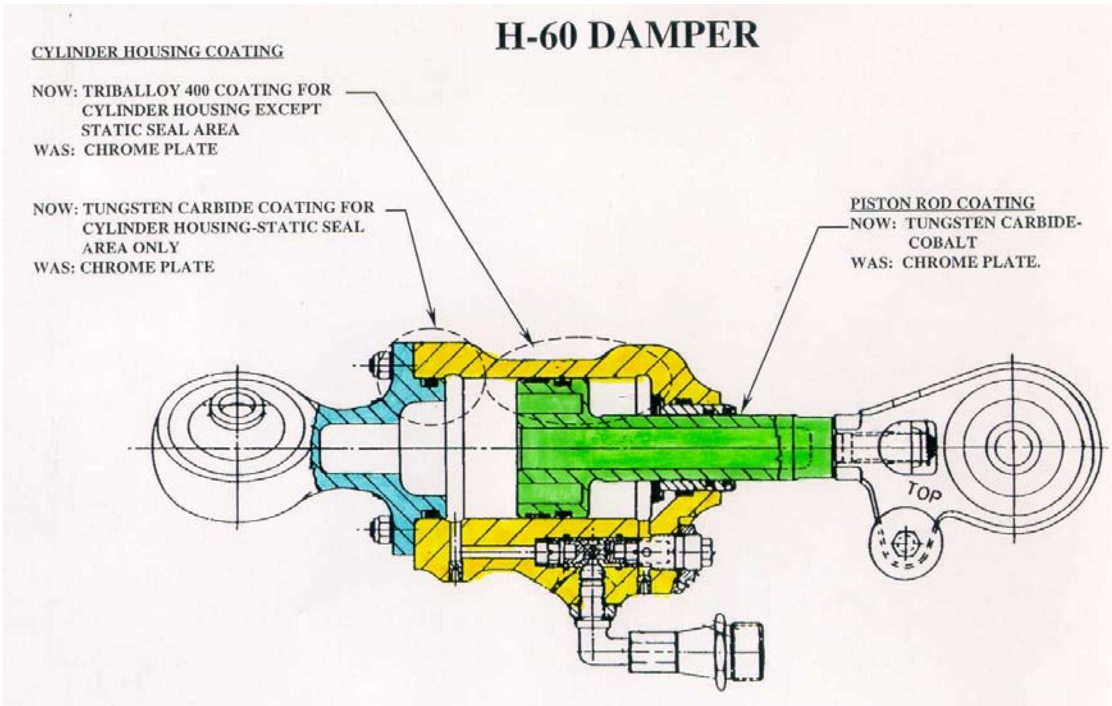



**Figure 8-2. H-60 helicopter blade damper with chrome alternative coatings (courtesy Praxair Surface Technology).**

At the April 2003 HCAT meeting in San Diego a special workshop was held involving the three SERDP ID coating development teams and the users, to assess the progress and performance of the three SERDP-funded ID coating technologies – plasma spray, nanophase Co alloy electroplating, and Electrospark Deposition. The Summary of this meeting is given in Appendix 4, while the table of comparative capabilities is shown in Table 8-1.

**Table 8-1. Summary of ID coating technologies - Plasma Spray, Nanophase Electroplating, Electrospark Deposition. (From 3-Team workshop – see Appendix 4.)**

| Application | Nano-Co | Plasma spray | ESD |
|---|---|---|---|
| Major strengths | Smooth, bath drop-in | Wear resistant, low waste | Repair, portable, difficult-to-reach areas |
| Large – LG outer cylinder | Good – scale up needed | Fast – diameter OK, any length can be provided | Very slow – not suitable |
| Short - dampers | Good – no scale up needed | Good – rapid, efficient | Good for repair |
| Small - pins | Can coat down to ½" ID | Not usable | Good, efficient, no masking |
| Thick build | Quite good – faster than Cr | Good – high rate | Not suitable, except small area repair |
| Thin dense or flash Cr | Good – efficient, smooth, nodular | Not suitable – too thick, rough | Not suitable – too rough |
| Local repair | Brush plate | Can be done | Very good, can be hand-held, transportable |

Of the three methods, nanophase electroplating has the widest application and is the closest to a direct drop-in (albeit requiring new power supplies). It can directly replace ID hard chrome, thin dense chrome, and brush plated chrome. This makes it a method that can be used for both D-level and I-level repair. Plasma spray coatings can provide adequate hardness and wear resistance, but not the very high wear resistance that HVOF gives to external surfaces. However, plasma spray is a fast process that avoids the need for a hydrogen bakeout, allowing faster depot turnaround. It is also a cost-effective ID coating for systems that already use HVOF for ODs. ESD is best for small areas and small diameters. Its principal application is for clean repair of small areas, including interiors and even re-entrant geometries.

Based on these findings we concluded that the best all-around replacement for ID chrome would be the nanophase electroplate. This approach was also supported by the JSF ESOH working group. The technology is being validated in ESTCP Project # PP-0411. However, ID plasma spray does remain an important alternative for those applications where turnaround time is critical or where thermal spray is already being used on other areas of the same component.

This page intentionally left blank.

# 9. Conclusions and Recommendations

**Performance:** The WC-based plasma spray coatings are an acceptable alternative to hard chrome for ID applications in diameters of 2.75” or above. In fact, given the performance of the F300 gun, the method appears practical for diameters as small as 1.6”. This makes the method viable for both utility actuators and flight surface actuators, but not for small IDs such as LTVD ID surfaces.

As expected from prior thermal spray coating experience, plasma spray coatings have higher porosity and are not as hard compared to HVOF coatings. Despite the fact that their residual stress is generally neutral to somewhat tensile, rather than highly compressive as HVOF coatings are, their fatigue performance is better than that of EHC.

**Materials:** In general, for optimum wear performance the carbides should be used. Of these, the WC-12Co material is the hardest, but the self fluxing carbides perform within the chrome envelope in most cases. With its low percentage of binder the WC-12Co is the most brittle of these coatings and is therefore more likely to crack on deposition or grinding. For areas such as pistons and IDs the best option is often Tribaloy. The advantage of this material for cylinder IDs is that it is more lubricious and somewhat softer, and not as likely to cause excessive piston wear. (Unfortunately its wear life is not as long as that of carbides.) A major advantage of using Tribaloy for piston heads (which can usually be HVOF sprayed) is that the head can be sprayed first and then plunge ground to form a sharp-edged O-ring groove. The carbides are too brittle for this, and also require a diamond wheel that cannot be used for the underlying steel.

Given the large range of thermal spray materials, carbides other than those tested here may perform equally well. For example, chrome carbides or one of the many other tungsten carbides not tested in this program may also be good options.

**ESOH issues:** The ESOH issues with plasma spray are essentially the same as with HVOF since both use similar powders. Co (which is part of the binder in several of the coatings tested) is not totally benign, but it is less toxic overall than either Cr or Ni [6]. An evaluation was performed of the ESOH issues surrounding the use of Co and of nanopowders (although it was ultimately concluded that nanopowder spray was not effective) and a summary is given in Appendix 5.

**Finishing:** In general it should be assumed that the surface finish should be the same as that used for HVOF rather than for EHC. Generally this requires that sealing surfaces have a 4μ” finish rather than the 16μ” typical of EHC. In addition a diamond wheel is needed to grind carbides.

**Sealing:** Since the team could not define *a-priori* the maximum porosity for hydraulics, it is uncertain whether these coatings may be used as-ground or whether they must be sealed with a standard polymer sealant (wipe-on wipe-off or vacuum impregnated). Given porosities generally in the 6-8% range it is almost certain that gas-over-fluid systems, such as landing gear, will need to be sealed. Sealing may or may not be necessary for other hydraulic systems.

**Equipment:** As shown in Appendix 3, spray rates for many ID guns are too low to make them cost-effective alternatives unless the chrome plating cost rises due to increased regulation, or there are other strong drivers such as turnaround time. The plasma gun model should be chosen to provide the highest spray rate consistent with the ID to be coated.

An ID plasma spray gun will fit onto a robotic arm in a standard thermal spray booth, and can usually run with the same powder feeders as those used for HVOF. This makes the plasma spray method directly complementary to the HVOF method.

In most of the work carried out in this project convenience has dictated a horizontal arrangement

in which the component to be coated is horizontally mounted on a lathe and rotates about the gun Vertical arrangements are also possible, as are arrangements in which the component to be coated remains stationary while the gun rotates using standard commercially-available rotating heads.

It is important to ensure that the system is rigid enough to prevent the gun touching the tube, which may damage the coating or short out the gun. This is especially an issue as the extension becomes longer for deeper IDs.

A test instrument such as the Fumespector is especially useful for designing additional air spray nozzles to minimize the overspray within an ID. However, it is important that any modification of this type by followed by an optimization of the spray parameters since modified gas sparging arrangements can affect the deposition conditions and coating quality.

The present lower limit on the diameter for coating with commercial guns is 1.6". New equipment is being developed that may permit much smaller diameters to be coated. After this work was completed a new HVOF gun has also come onto the market. This equipment should make it possible to apply HVOF coatings to IDs down to about 4", making ID HVOF commercially viable for almost all landing gear outer cylinder IDs and many utility actuators (but still too large for most flight surface actuators).

These developments are described in Appendix 7.

# REFERENCES


1. "The Effect of Off-angle Spraying on the Structure and Properties of HVOF WC-Co-Cr", P. Ruggiero, M. Froning, Air Force Plating Working Group, June 2003.
2. "Chrome Replacements for Internals and Small Parts", K.O. Legg, funded by JSF IPT (January 1999).
3. See, for example, "NLOS Hard Chrome Alternatives Update", J. Kolek, HCAT Program Review, San Diego (April 2003).
4. "Progress in the Development of Nanostructured Coatings for Wear Protection: a Literature Review", Salim Bouaricha, NRC-IMI (November 2003).
5. "Hard Chrome Coatings: Advanced Technology for Waste Elimination", Keith O. Legg. Final report, DARPA Contract # MDA972-93-1-0006 (1997).
6. "Cobalt Environmental and Industrial Health Risk Assessment: A Case Study", C. Tomljanovic, J. Napotnik, and T. Gittings.

This page intentionally left blank.

# Appendix 1. METALLOGRAPHIC PREPARATION AND POROSITY – NRC

In order to achieve consistent and reproducible metallographic preparation, IMI has developed a standardized method for cutting, mounting and polishing coating samples. The following is a description of the major steps required for such a preparation.

- **Sample cutting:**

  Coating must be cut using a high-speed cutting machine with the coating under compression.

  Use an HC 15 Diamond wheel

  Load on the sample: 700 gr

  Speed of the blade: 4000 rpm.

  Clean with ethanol or a solvent and dry

- **Sample Mounting using vacuum infiltration technique:**

  Preheat samples and epoxy to 150°F (60°C) (Caldofix or Epofix from Struers may be used). Do not heat Epofix for more than 2 minutes

  Put sample in mold (you may apply a thin film of silicone de-moulder)

  Mix epoxy with hardener

  Impregnate under vacuum

  Maintain vacuum (200 mbar) until bubbles disappear (5 min )

  Fill up mold with epoxy and let cure (room temp 8 hours for Epofix or 80°C 2 hours for Caldofix)

- **Sample polishing (Hard material) 6 mounts:**

  First, ensure the mounts are hard (fully set)

  SiC, 220 grit, 200 N., 300 rpm, 30 sec. (water as lubricant). Repeat until sample is flat. (Usually, three papers are enough.)

  Wash (brush-soap-water) + Ultrasonic bath 15 sec.

  DP Allegro, 9 microns, 200 N., 150 rpm, 240-300 sec.(4-5 min.). Add lubricant to keep surface shiny.(DP-Blue or DP-Green as lubricant)

  Wash (brush-soap-water) + Ultrasonic bath 15 sec.

  DP Dac, 3 microns, 200 N., 150 rpm, 300 sec. (5 min.) (DP-Blue or as lubricant)

  Wash (brush-soap-water) + Ultrasonic bath 15 sec

  OP-Chem, OP-A(50% water), 150 rpm, 30 sec

  Wash (brush-soap-water) + Ultrasonic bath 15 sec+ Q Tip soap water + rinse

  (Note: you may use MD products instead of DP).

# Appendix 2. CHARACTERIZATION OF PLASMA SPRAYED COATINGS

There are a large number of WC powder formulations by different powder manufacturers, of which the Sulzer Metco powders can be found on the Sulzer Metco web site. In the course of optimizing ID WC plasma spray Sulzer Metco evaluated many of these. This Appendix is a Sulzer Metco report on the testing of various WC-Co powders using ID guns.

Figure 1 shows an initial “standard” WC-17Co from the SM F100 gun, made by spraying Diamalloy 2005 powder, which is used for most HVOF WC-17Co coatings.

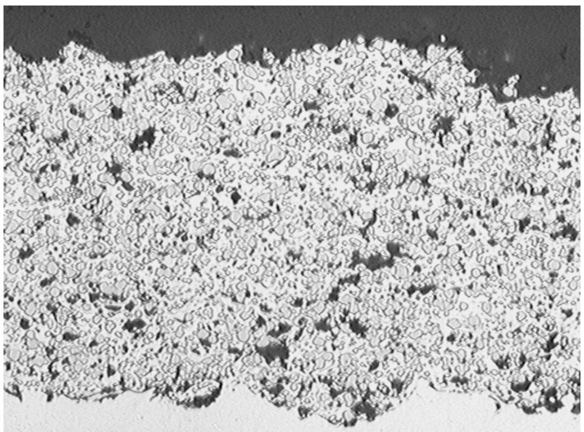


Fig. 1: Diamalloy 2005; plasma sprayed with F-100; Run Number: 91018-2; 200x unetched

Porosity: 7.1%

Macrohardness (15N): 85.8

Microhardness ($HV_{300}$): 840 average

# 1. Diamalloy 2006 (WC-17Co)

Table 1 shows the tests with Diamalloy 2006, which were carried out since the report 00699-2/Part II was issued. The tests were carried out to determine the influence of the added hydrogen gas on coating structure. Note the Argon and helium flows remain constant, as well as the current level.

Table 1: Tests run with Diamalloy 2006

| Run Number | Gun Type | Powder | Primary gas flow | Secondary gas flow | Tertiary gas flow ($H_2$) | Current [A] | Voltage [V] |
|---|---|---|---|---|---|---|---|
| 91220-2 | F-100 | 2006NS | 85 SLPM | 10 SLPM | 0.5 SLPM | 350 | 36 |
| 91220-3 | F-100 | 2006NS | 85 SLPM | 10 SLPM | 2 SLPM | 350 | 43.7 |
| 91221-1 | F-100 | 2006NS | 85 SLPM | 10 SLPM | 4 SLPM | 350 | 48.5 |
| 91226-1 | F-100 | 2006NS | 85 SLPM | 10 SLPM | 6 SLPM | 350 | 52.5 |
| 91226-2 | F-100 | 2006NS | 85 SLPM | 10 SLPM | 8 SLPM | 350 | 54.5 |

From the above table, the best parameter was run number 91226-2 (figure 2), which is a significant improvement in porosity (9.7% versus 12%) to the previous defined Diamalloy 2006 standard (figure 4). However, there was some cracking noted. A second best would be 91226-1 (figure 3). The porosity of this sample is slightly higher (10.9%) than 91226-2 (figure 2), however the microhardness is slightly higher than 91226-2, and no cracks were detected in this sample. The Porosity of sample number 91226-1 was still an improvement over 91102-1 (10.9% versus 12%). The microhardness of these new samples (91226-2 and 91226-1) dropped significantly as compared to the earlier trial (91102-1), yet the macrohardness remained virtually unchanged. Microhardness of 91226-2 was measured at 678 $HV_{300}$ average (compared to 1120 $HV_{300}$ average for 91102-1), and the macrohardness was measured as 83.8 15N average. Microhardness of 91226-1 was measured at 717 $HV_{300}$ average, and the macrohardness was measured as 83.5 15N average.

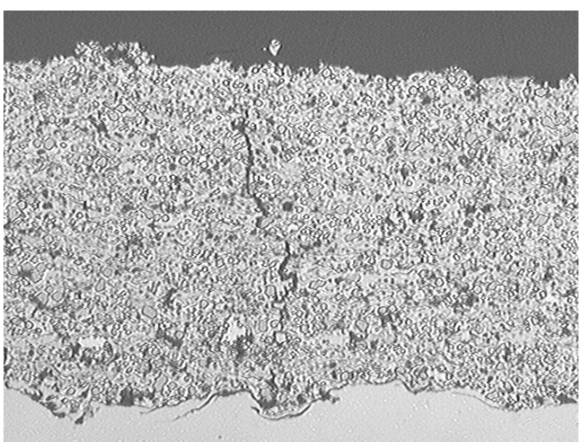


Fig. 2: Diamalloy 2006; sprayed with F-100;

Run Number: 91226-2; 200x unetched

Porosity 9.7%

Macrohardness (15N): 83.8

Microhardness ($HV_{300}$): 678 average

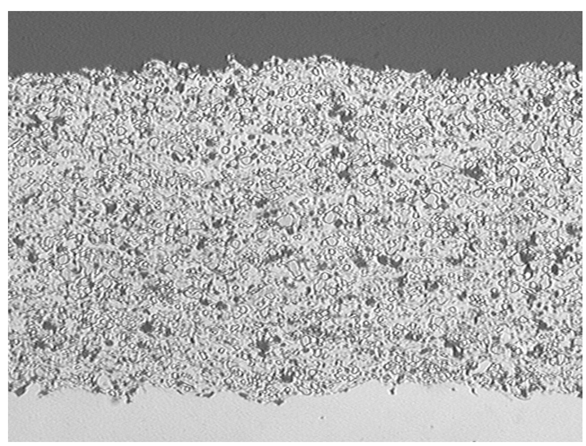


Fig. 3: Diamalloy 2006; sprayed with F-100

Run Number: 91226-1; 200x unetched

Porosity 10.9%

Macrohardness (15N): 83.5

Microhardness ($HV_{300}$): 717 average

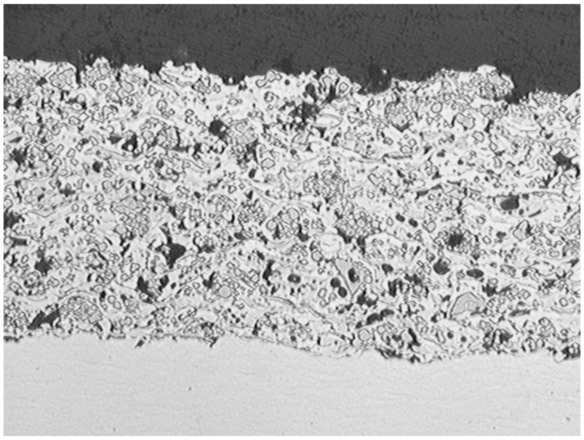


Fig. 4: Diamalloy 2006; sprayed with F-100

Run Number: 91102-1; 200x unetched

Porosity: 12%

Macrohardness (15N): 82.8

Microhardness ($HV_{300}$): 1120 average

# 2. Diamalloy 2005NS (WC-17Co)

Due to the poor results obtained with Diamalloy 2006 in the F-100 gun in the past, Diamalloy 2005NS samples were also processed in the same manner as described in section 1.1 above. Table 2 shows this test plan.

Table 2: Tests run with Diamalloy 2005NS

| Run Number | Gun Type | Powder | Primary gas flow | Secondary gas flow | Tertiary gas flow ($H_2$) | Current [A] | Voltage [V] |
|---|---|---|---|---|---|---|---|
| 91201-1 | F-100 | 2005NS | 85 SLPM | 10 SLPM | 0.5 SLPM | 350 | 38.4 |
| 91201-2 | F-100 | 2005NS | 85 SLPM | 10 SLPM | 2 SLPM | 350 | 43.2 |
| 91201-3 | F-100 | 2005NS | 85 SLPM | 10 SLPM | 4 SLPM | 350 | 47.8 |
| 91201-4 | F-100 | 2005NS | 85 SLPM | 10 SLPM | 6 SLPM | 350 | 52.2 |
| 91201-5 | F-100 | 2005NS | 85 SLPM | 10 SLPM | 8 SLPM | 350 | 54.5 |

From the above table, the best parameter was run number 91201-3 (figure 5). A second best would be 91201-1 (figure 6). The porosity of sample 91201-1 (figure 6) is slightly higher than 91201-3 (figure 5), however the microhardness is also higher. The porosity of sample number 91201-3 was lower than 91201-1 (8.6% versus 11.2%), and both were higher than the previous standard, 91018-2, at 7.1% (figure 7). The microhardness of 91201-3 (figure 5) dropped slightly as compared to 91018-2 (figure 7), however the microhardness of 91201-1 (figure 6) was slightly higher. The macrohardness also dropped slightly for both samples as compared to 91018-2 (figure 7). Microhardness of 91201-3 was measured at 704 $HV_{300}$ average and the macrohardness was measured as 82.0 15N average. Microhardness of 91201-1 was measured at 847 $HV_{300}$ average, and the macrohardness was measured as 84.3 15N average.

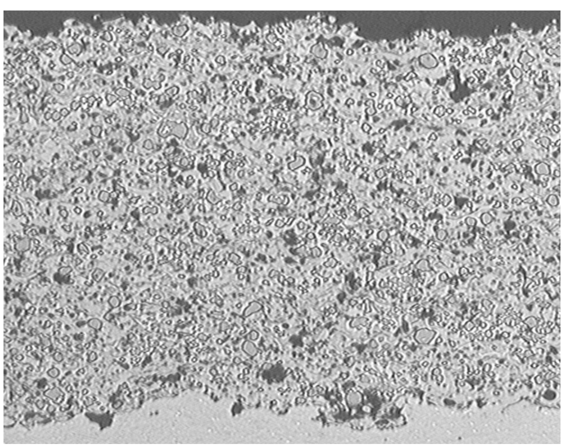


Fig. 5: Diamalloy 2005; sprayed with F-100;

Run Number: 91201-3; 200x unetched

Porosity: 8.6%

Macrohardness (15N): 82.0

Microhardness ($HV_{300}$) 704 average

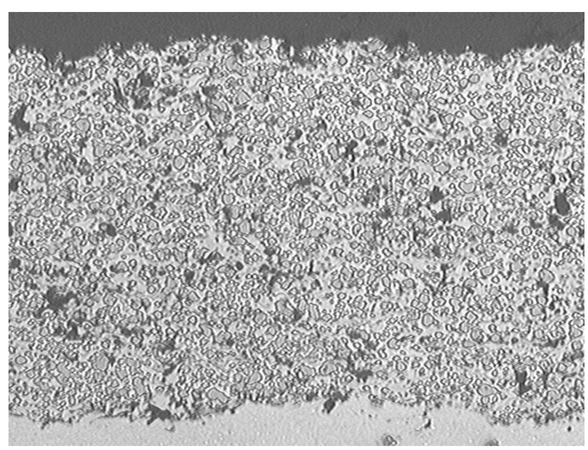


Fig. 6: Diamalloy 2005, sprayed with F-100

Run number 91201-1, 200x unetched

Porosity 11.2%

Macrohardness (15N) 84.3

Microhardness ($HV_{300}$) 847 average

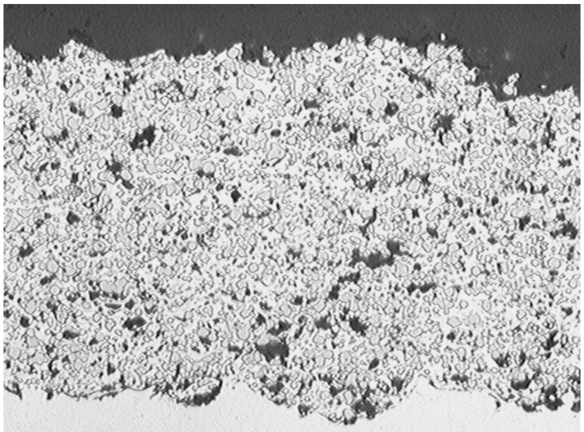


Fig. 7: Diamalloy 2005; plasma sprayed with F-100; Run Number: 91018-2; 200x unetched

Porosity: 7.1%

Macrohardness (15N): 85.8

Microhardness ($HV_{300}$): 840 average

# 3. Metco 73F (WC-17Co)

Metco 73F has the same chemical composition as Diamalloy 2005 and Diamalloy 2006, however it has a larger grain size distribution. Due to the poor performance of the finer grain size distribution of the Diamalloy 2006, 73F was run in an attempt to improve the coating structure. The same parameters run with Diamalloy 2005 and Diamalloy 2006 (in tables 1 and 2 respectively, above) have been run with the Metco 73F for direct comparison. Parameters for Metco 73F are listed in table 3, below.

Table 3: Tests run with Metco 73F

| Run Number | Gun Type | Powder | Primary gas flow | Secondary gas flow | Tertiary gas flow ($H_2$) | Current [A] | Voltage [V] |
|---|---|---|---|---|---|---|---|
| 911001-1 | F-100 | 73F | 85 SLPM | 10 SLPM | 0.5 SLPM | 350 | 37 |
| 911001-2 | F-100 | 73F | 85 SLPM | 10 SLPM | 2 SLPM | 350 | 43.5 |
| 911001-3 | F-100 | 73F | 85 SLPM | 10 SLPM | 4 SLPM | 350 | 48.4 |
| 911001-4 | F-100 | 73F | 85 SLPM | 10 SLPM | 6 SLPM | 350 | 52 |
| 911001-5 | F-100 | 73F | 85 SLPM | 10 SLPM | 8 SLPM | 350 | 55 |

From the above table, the best parameter was run number 911001-4 (figure 8). A second best would be 911001-1 (figure 9). The porosity of sample 911001-1 (figure 9) is slightly higher than 911001-4 (figure 8), however the microhardness is also higher. The porosity of sample number 911001-4 was 7.0% and the porosity of sample number 911001-1 was 7.2%. The microhardness of 911001-4 was measured at 611 $HV_{300}$ average and the macrohardness was measured as 81.9 15N average. Microhardness of 911001-1 was measured at 791 $HV_{300}$ average, and the macrohardness was measured as 84.5 15N average. Some cracks were detected in sample number 911001-4, but not in sample number 911001-1. Photomicrographs are below.

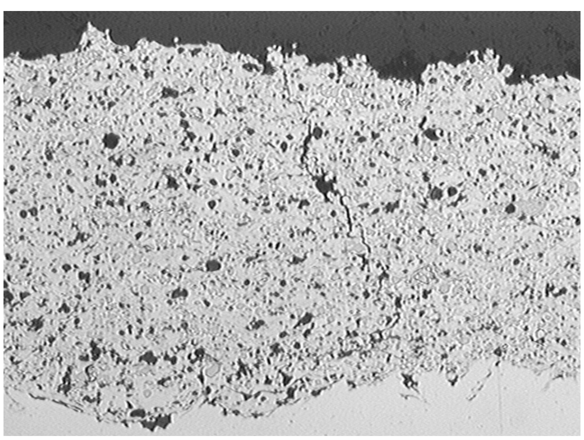


Fig. 8: Metco 73F; with F-100; (6 $H_2$)

Run Number: 911001-4; 200x unetched

Porosity: 7.0%

Macrohardness (15N): 81.9

Microhardness ($HV_{300}$): 611 average

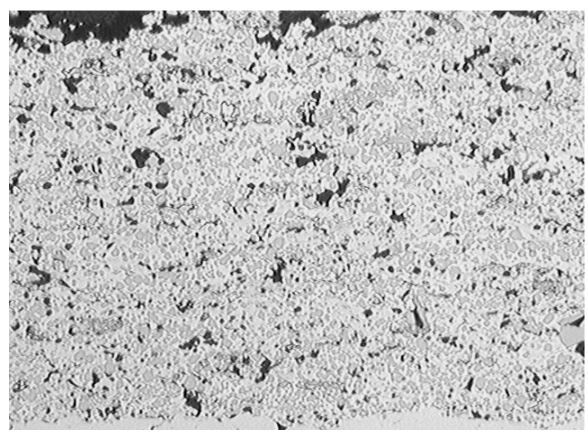


Fig. 9: Metco 73F; with F-100 (0.5 $H_2$)

Run Number: 911001-1, 200x unetched

Porosity: 7.2%

Macrohardness (15N): 84.5

Microhardness ($HV_{300}$): 791 average

The polishing of these materials proved to be quite challenging. The goal was to find the most accurate preparation method to prevent “smearing” as well as “pull-out”. Either of these conditions could lead to inaccurate evaluation of the coatings.[1]

Additional coatings were sprayed with the three-gas parameter used for the Diamalloy 2005 and Diamalloy 2006, as outlined in tables 1 and 2, above. Only two of the five parameters listed were run with each material, to save time. The lowest (0.5 l/min) as well as the highest (8 l/min) hydrogen flows were run for each material. The results of these tests are broken down by material below.

1 Note: Polishing methods and porosity measurement were developed by NRC for this program as a result of these early findings. The specifications developed by NRC are given in Appendix 1.

## 4. Sulzer Metco 5803 ((WC 12Co) 25(Ni-Based Superalloy))

Sulzer Metco 5803 was sprayed, sectioned and prepared for metallographic evaluation. The microhardness was determined to be 571 ($HV_{300}$) for the 0.5 l/min hydrogen flow (sample 911101-3), and 635 ($HV_{300}$) for the 8 l/min flow (sample 911101-2). Macrohardness was determined to be 82.2 (15N) for the 0.5 l/min, and 82.5 (15N) for the 8 l/min hydrogen flow. Porosity of the 0.5 l/min sample was determined to be 3.6%, and 3.2% for the 8 l/min sample. Some cracking was noted with the 8 l/min hydrogen flow. Photomicrographs of these coatings are below, figures 10 and 11.

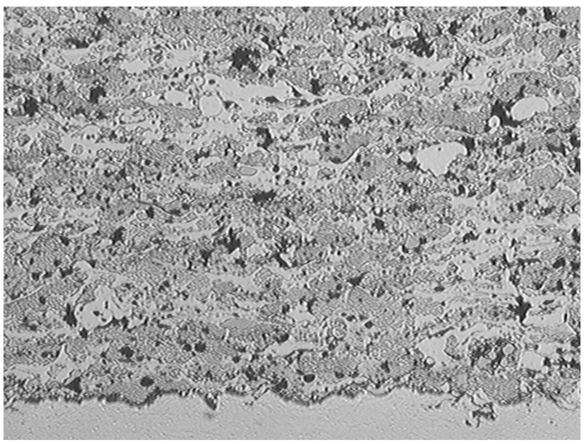


Fig. 10: SM 5803; sprayed with F-100; (0.5 $H_2$)

Run Number: 911101-3; 200x unetched

Porosity: 3.6%

Macrohardness (15N): 82.2

Microhardness ($HV_{300}$): 571 average

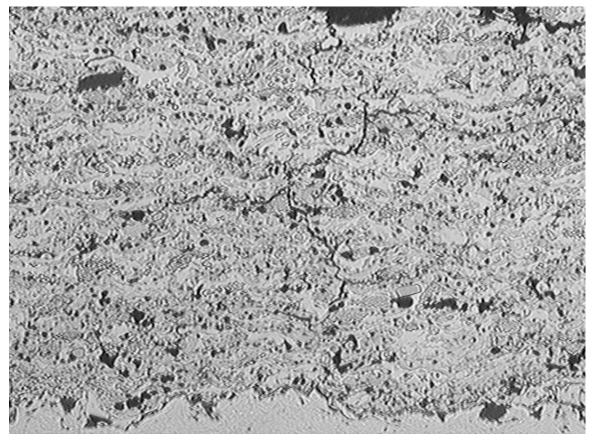


Fig. 11: SM 5803; sprayed with F-100 (8 $H_2$)

Run Number: 911101-2, 200x unetched

Porosity: 3.2%

Macrohardness (15N): 82.5

Microhardness ($HV_{300}$): 635 average

# 5. Metco 439NS-2 (WC-12Co self fluxing)

Metco 439NS-2 was sprayed, sectioned and prepared for metallographic evaluation. The microhardness was determined to be 619 ($HV_{300}$) for the 0.5 l/min flow (sample 911101-4), and 644 ($HV_{300}$) for the 8 l/min flow (sample 911101-5). Macrohardness was determined to be 81.8 (15N) for the 0.5 l/min, and 79.7 (15N) for the 8 l/min hydrogen flow. Porosity of the 0.5 l/min sample was determined to be 2.8%, and <1% for the 8 l/min sample. Some cracking was noted with the 8 l/min hydrogen flow. Photomicrographs of these coatings are below, figures 12 and 13.

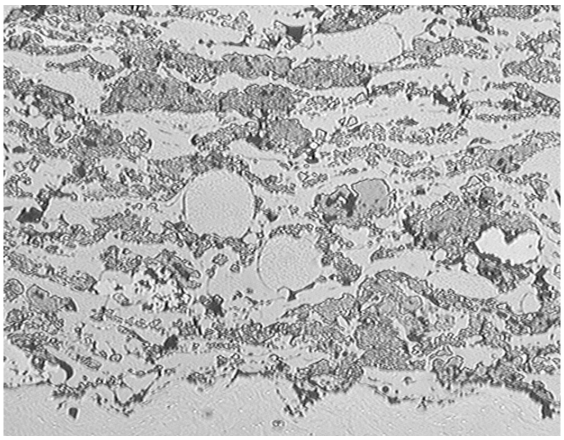


Fig. 12: Metco 439NS-2; with F-100; (0.5 $H_2$)

Run Number: 911101-4; 200x unetched

Porosity: 2.8%

Macrohardness (15N): 81.8

Microhardness ($HV_{300}$): 619 average

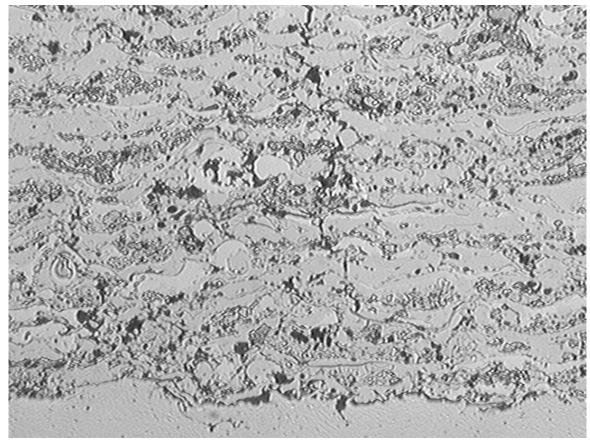


Fig. 13: Metco 439NS-2; with F-100 (8 $H_2$)

Run Number: 911101-5, 200x unetched

Porosity: <1%

Macrohardness (15N): 79.7

Microhardness ($HV_{300}$): 644 average

# 6. Sulzer Metco 5843 (WC-10Co-4Cr)

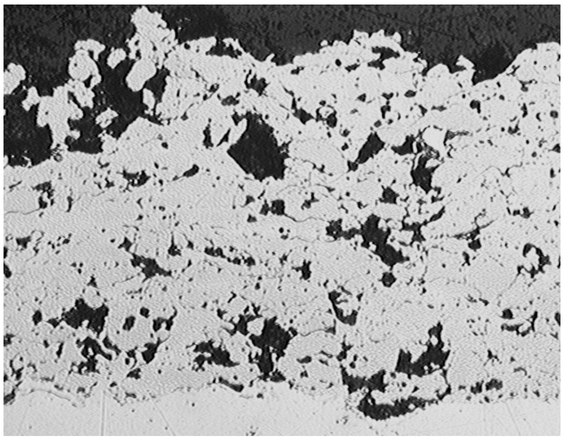


Fig. 14: SM 5843; with F-100; (0.5 $H_2$)

Run Number: 911101-6; 200x unetched

Porosity: 11.1%

Macrohardness (15N): 83.2

Microhardness ($HV_{300}$): 897 average

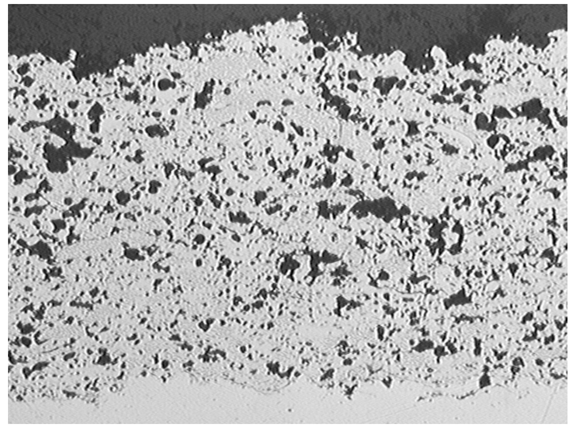


Fig. 15: SM 5843; with F-100 (8 $H_2$)

Run Number: 911101-7, 200x unetched

Porosity: 10.3%

Macrohardness (15N): 75.9

Microhardness ($HV_{300}$): 616 average

Sulzer Metco 5843 was sprayed, sectioned and prepared for metallographic evaluation. The microhardness was determined to be 897 ($HV_{300}$) for the 0.5 l/min flow (sample 911001-6), and 616 ($HV_{300}$) for the 8 l/min flow (sample 911001-7). Macrohardness was determined to be 83.2 (15N) for the 0.5 l/min, and 75.9 (15N) for the 8 l/min hydrogen flow. Porosity of the 0.5 l/min sample was determined to be 11.1% and 10.3% for the 8 l/min sample. No cracking was noted with either hydrogen flow. Photomicrographs of these coatings are shown in figures 14 and 15 above.

# 7. Sulzer Metco 5847 (WC-10Co-4Cr)

Sulzer Metco 5847 was sprayed, sectioned and prepared for metallographic evaluation. The microhardness was determined to be 656 ($HV_{300}$) for the 0.5 l/min flow (sample 911001-8), and 665 ($HV_{300}$) for the 8 l/min flow (sample 911001-9). Macrohardness was determined to be 82.8 (15N) for the 0.5 l/min, and 80.5 (15N) for the 8 l/min hydrogen flow. Porosity of the 0.5 l/min sample was determined to be 12.5% and 8.0% for the 8 l/min sample. No cracking was noted with either hydrogen flow. Photomicrographs of these coatings are below, figures 16 and 17.

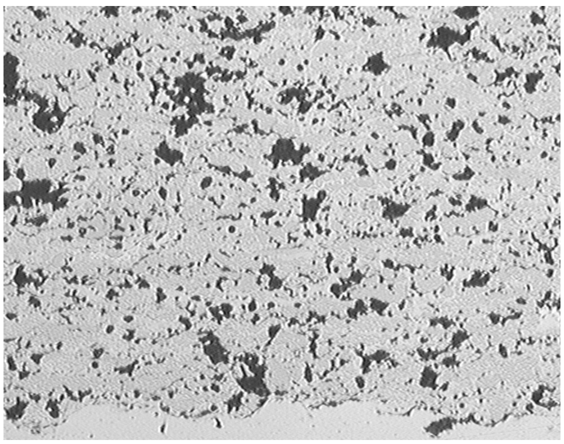


Fig. 16: SM 5847; with F-100; (0.5 $H_2$)

Run Number: 911101-8; 200x unetched

Porosity: 12.5%

Macrohardness (15N): 82.8

Microhardness ($HV_{300}$): 656 average

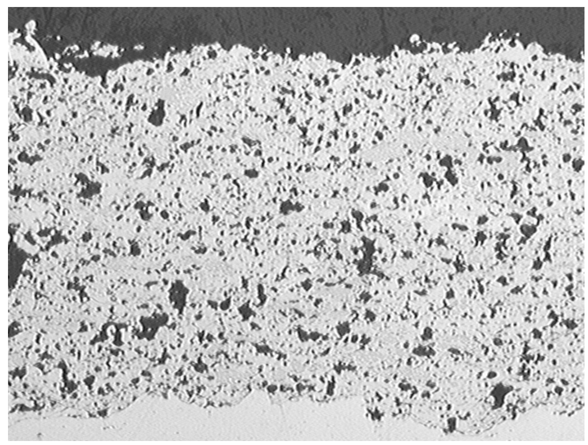


Fig. 17: SM 5847; with F-100 (8 $H_2$)

Run Number: 911101-9, 200x unetched

Porosity: 8.0%

Macrohardness (15N): 80.5

Microhardness ($HV_{300}$): 665 average

# 8. Diamalloy 2002 (WC-12Co self fluxing)

Diamalloy 2002 was sprayed, sectioned and prepared for metallographic evaluation. The microhardness was determined to be 742 ($HV_{300}$) for the 0.5 l/min flow (sample 911001-10), and 670 ($HV_{300}$) for the 8 l/min flow (sample 911001-11). Macrohardness was determined to be 83.5 (15N) for the 0.5 l/min, and 84.9 (15N) for the 8 l/min hydrogen flow. Porosity of the 0.5 l/min sample was determined to be 4.1%, and <1% for the 8 l/min sample. The majority of the area of the 8 l/min sample was determined to be <1% porosity, however it should be noted there were local areas which approached 3% porosity. No cracking was noted with either hydrogen flow, however delamination of the 0.5 l/min sample and partial delamination of the 8 l/min sample was noted. Photomicrographs of these coatings are below, figures 18 and 19.

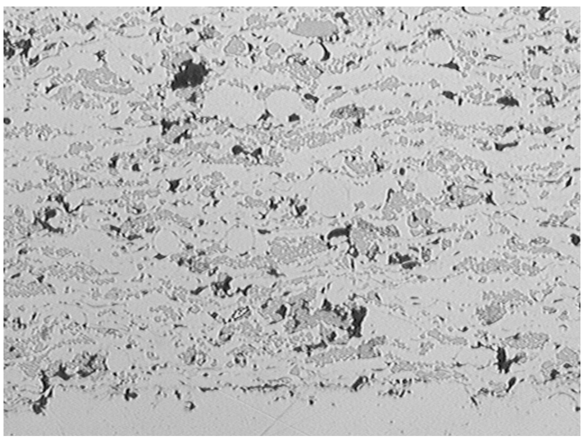


Fig. 18: Diamalloy 2002; with F-100; (0.5 $H_2$)

Run Number: 911001-10; 200x unetched

Porosity: 4.1%

Macrohardness (15N): 83.5

Microhardness ($HV_{300}$): 742 average

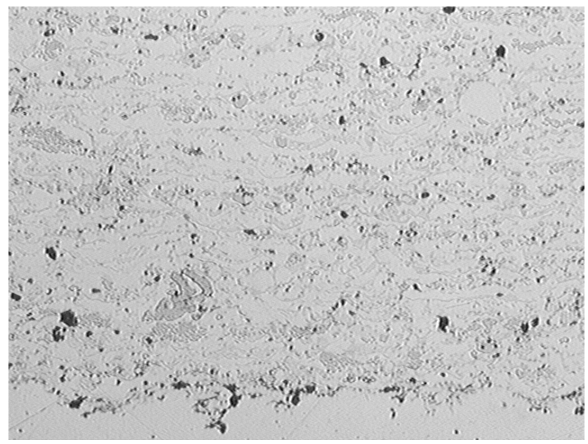


Fig. 19: Diamalloy 2002; with F-100 (8 $H_2$)

Run Number: 911001-11, 200x unetched

Porosity: <1%

Macrohardness (15N): 84.9

Microhardness ($HV_{300}$): 670 average

# 9. Diamalloy 2003 (WC-12Co)

Diamalloy 2003 was sprayed, sectioned and prepared for metallographic evaluation. The microhardness was determined to be 655 ($HV_{300}$) for the 0.5 l/min flow (sample 911101-6), and 779 ($HV_{300}$) for the 8 l/min flow (sample 911101-7). Macrohardness was determined to be 86.4 (15N) for the 0.5 l/min, and 84.4 (15N) for the 8 l/min hydrogen flow. Porosity of the 0.5 l/min sample was determined to be 10.5% and 4.2% for the 8 l/min sample. No cracking was noted with either hydrogen flow, and no delamination was noted. Photomicrographs of these coatings are below, figures 20 and 21.

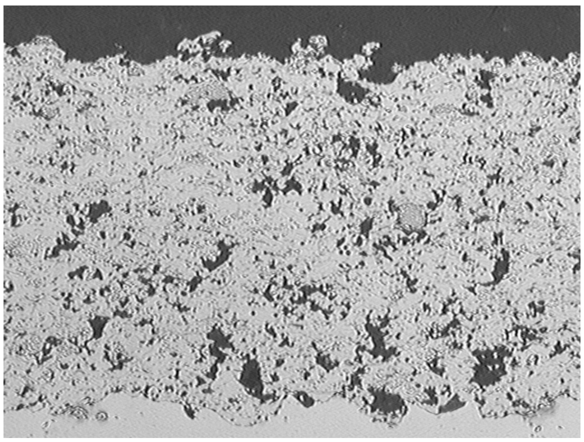


Fig. 20: Diamalloy 2003; with F-100; (0.5 $H_2$)

Run Number: 911101-6; 200x unetched

Porosity: 10.5%

Macrohardness (15N): 86.4

Microhardness ($HV_{300}$): 655 average

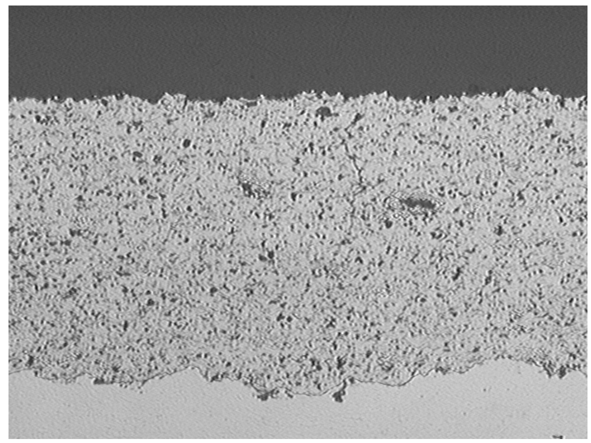


Fig. 21: Diamalloy 2003; with F-100 (8 $H_2$)

Run Number: 911101-7, 200x unetched

Porosity: 4.2%

Macrohardness (15N): 84.4

Microhardness ($HV_{300}$): 779 average

# 10. Metco 439NS (WC-12Co self fluxing)

Metco 439NS was sprayed, sectioned and prepared for metallographic evaluation. The microhardness was determined to be 605 ($HV_{300}$) for the 0.5 l/min flow (sample 911201-1), and 552 ($HV_{300}$) for the 8 l/min flow (sample 911201-2). Macrohardness was determined to be 79.0 (15N) for the 0.5 l/min, and 76.6 (15N) for the 8 l/min hydrogen flow. Porosity of the 0.5 l/min sample was determined to be 8.7% and 6.1% for the 8 l/min sample. No cracking was noted with the 0.5 l/min flow, however the 8 l/min flow did show some cracks. No delamination was noted with either flow. Photomicrographs of these coatings are below, figures 22 and 23.

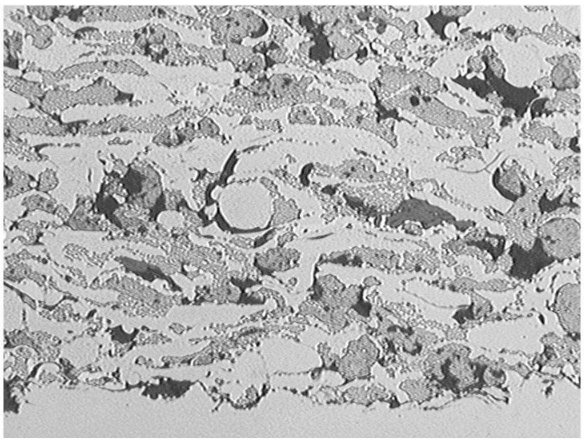


Fig. 22: Metco 439NS; with F-100; (0.5 $H_2$)

Run Number: 911201-1; 200x unetched

Porosity: 8.7%

Macrohardness (15N): 79.0

Microhardness ($HV_{300}$): 605 average

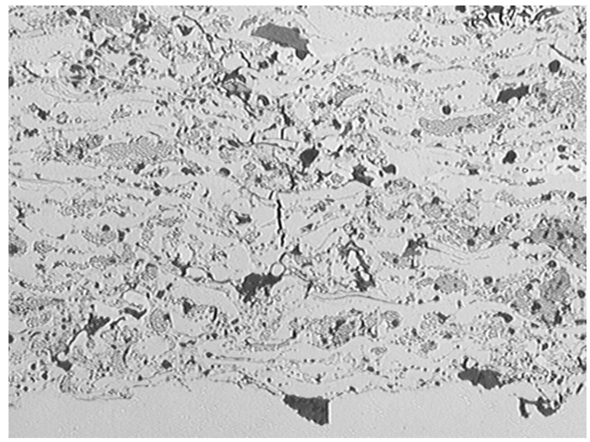


Fig. 23: Metco 439NS; with F-100 (8 $H_2$)

Run Number: 911201-2, 200x unetched

Porosity: 6.1%

Macrohardness (15N): 76.6

Microhardness ($HV_{300}$): 552 average

# 11. Sulzer Metco 5810 (WC-12Co)

Sulzer Metco 5810 was sprayed, sectioned and prepared for metallographic evaluation. The microhardness was determined to be 631 ($HV_{300}$) for the 0.5 l/min flow (sample 911201-3), and 524 ($HV_{300}$) for the 8 l/min flow (sample 911201-4). Macrohardness was determined to be 81.0 (15N) for the 0.5 l/min, and 77.4 (15N) for the 8 l/min hydrogen flow. Porosity of the 0.5 l/min sample was determined to be 17.2% and 11.3% for the 8 l/min sample. No cracking was noted with either flow, and no delamination was noted. Photomicrographs of these coatings are below, figures 24 and 25.

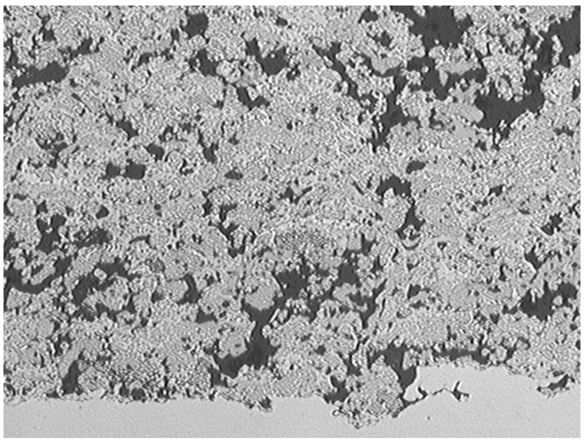


Fig. 24: SM 5810; with F-100; (0.5 $H_2$)

Run Number: 911201-3; 200x unetched

Porosity: 17.2%

Macrohardness (15N): 81.0

Microhardness ($HV_{300}$): 631 average

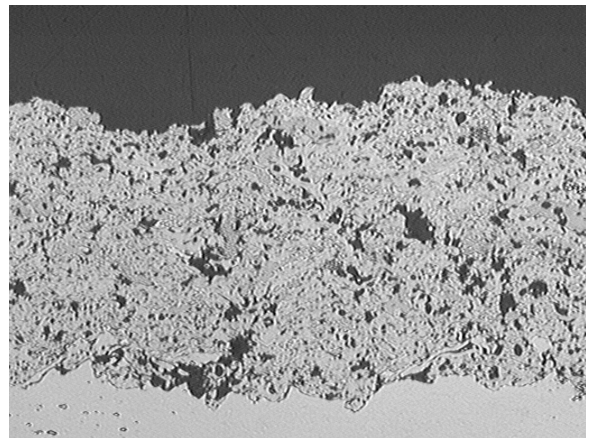


Fig. 25: SM 5810; with F-100 (8 $H_2$)

Run Number: 911201-4, 200x unetched

Porosity: 11.3%

Macrohardness (15N): 77.4

Microhardness ($HV_{300}$): 524 average

# 12. Sulzer Metco 5848 (WC-10Co4Cr)

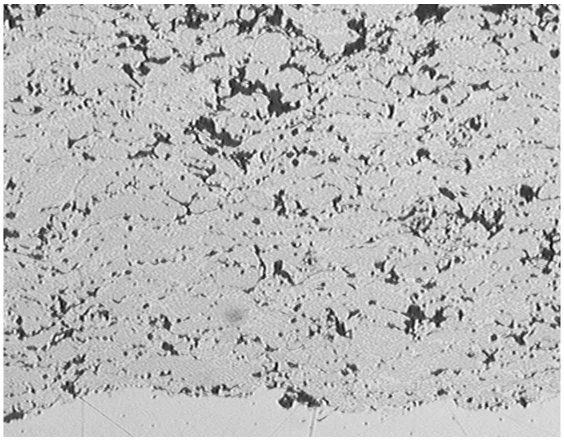


Fig. 26: SM 5848; with F-100; (0.5 $H_2$)

Run Number: 911201-5; 200x unetched

Porosity: 11.0%

Macrohardness (15N): 85.0

Microhardness ($HV_{300}$): 802 average

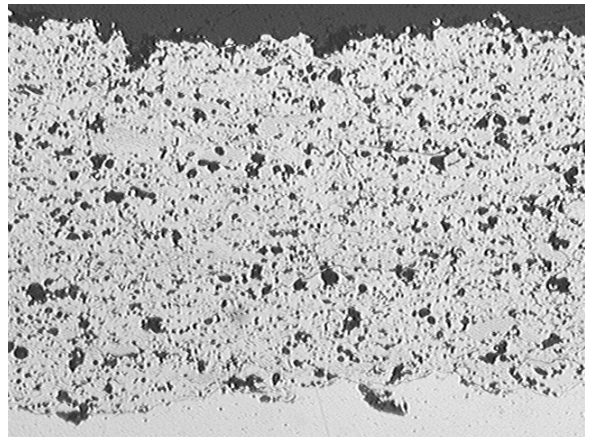


Fig. 27: SM 5848; with F-100 (8 $H_2$)

Run Number: 911201-6, 200x unetched

Porosity: 10.8%

Macrohardness (15N): 76.8

Microhardness ($HV_{300}$): 538 average

Sulzer Metco 5848 was sprayed, sectioned and prepared for metallographic evaluation. The microhardness was determined to be 802 ($HV_{300}$) for the 0.5 l/min flow (sample 911201-5), and 538 ($HV_{300}$) for the 8 l/min flow (sample 911201-6). Macrohardness was determined to be 85.0 (15N) for the 0.5 l/min, and 76.8 (15N) for the 8 l/min hydrogen flow. Porosity of the 0.5 l/min sample was determined to be 11.0% and 10.8% for the 8 l/min sample. Some fine cracking was noted with the 0.5 l/min hydrogen flow, yet none were detected with the 8 l/min flow. Fine delaminations were detected with the 8 l/min flow that were not seen with the 0.5 l/min flow. Photomicrographs of these coatings are above, figures 26 and 27.

# 13. Sulzer Metco 5826 (WC-17Co)

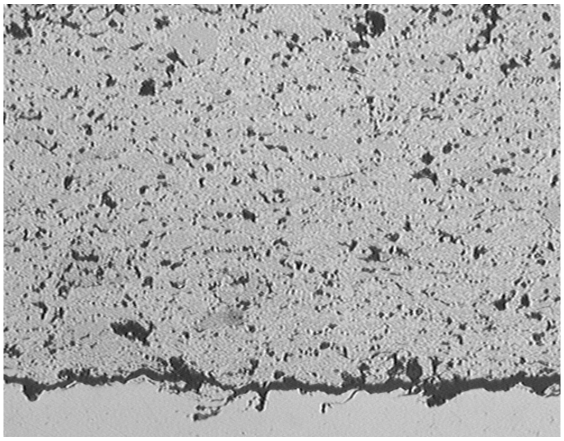


Fig. 28: SM 5826; with F-100; (0.5 $H_2$)

Run Number: 911501-1; 200x unetched

Porosity: 9.1%

Macrohardness (15N): 86.0

Microhardness ($HV_{300}$): 692 average

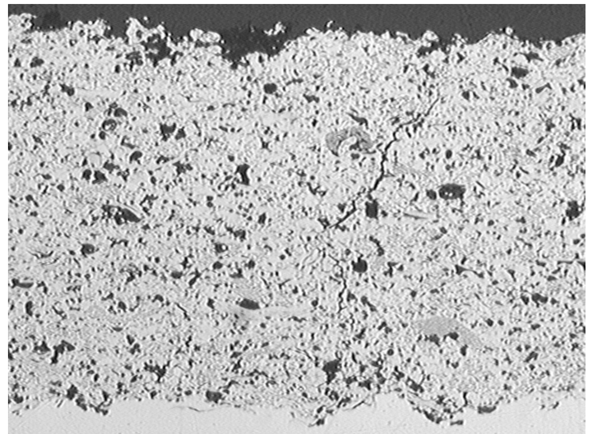


Fig. 29: SM 5826; with F-100 (8 $H_2$)

Run Number: 911501-2, 200x unetched

Porosity: 12.6%

Macrohardness (15N): 76.8

Microhardness ($HV_{300}$): 529 average

Sulzer Metco 5826 was sprayed, sectioned and prepared for metallographic evaluation. The microhardness was determined to be 692 ($HV_{300}$) for the 0.5 l/min flow (sample 911501-1), and 529 ($HV_{300}$) for the 8 l/min flow (sample 911501-2). Macrohardness was determined to be 86.0 (15N) for the 0.5 l/min, and 76.8 (15N) for the 8 l/min hydrogen flow. Porosity of the 0.5 l/min sample was determined to be 9.1% and 12.6% for the 8 l/min sample. No cracking was noted with either the 0.5 l/min or 8 l/min hydrogen flow. The 0.5 l/min sample delaminated, but the 8 l/min sample was well bonded. Photomicrographs of these coatings are above, figures 28 and 29.

# 14. Other materials

In addition to the tungsten carbides, Sulzer Metco evaluated a number of other materials with the aim of choosing the most wear-resistant option. Ten additional ceramic and carbide materials were deposited on IDs using the F210 ID gun and tested for abrasion and erosion, as shown below, but none showed more promise than the Diamalloy 2002 and 2003 chosen for optimization in the program.

**Abrasion/erosion test data for potential alternative hard coatings (Sulzer Metco).**

| | | Rubber wheel | | | Low angle blast erosion | | |
|---|---|---|---|---|---|---|---|
| Coating | Chemistry | Test result | Wear depth (Almen gage) | Volume loss (mm3) | Mass loss (gm) | Wear depth (ball micrometer) | Volume loss (mm3) |
| 82VF-NS | $Cr_3C_2$ 7(Ni 20Cr) | FAIL | 0.02 | 130.65 | 0.591 | 0.0084 | 98.5 |
| 71VF-NS | $W_2C$ / WC 12Co | Pass | 0.0144 | 63.77 | 0.348 | 0.0045 | 27.84 |
| D 3007 | $Cr_3C_2$ 20(Ni 20Cr) | Pass | 0.0024 | 16.23 | 0.145 | 0.0035 | 22.41 |
| SUME flux | Proprietary coating | Pass | 0.0042 | 29.32 | 0.143 | 0.0049 | 25.91 |
| D 2006 | WC 17Co | Pass | 0.004 | 21.38 | 0.235 | 0.0027 | 18.8 |
| 131VF | $Al_2O_3$ $40TiO_2$ | Pass | 0.0111 | 85.43 | 0.241 | 0.0106 | 68.86 |
| AE 7727 | $Al_2O_3$ $60ZrO_2$ | Pass | 0.0029 | 17.04 | 0.108 | 0.0041 | 25.96 |
| 136F | $Cr_2O_3$ $5SiO_2$ $3TiO_2$ | Pass | 0.0131 | 67.02 | 0.141 | 0.005 | 28.78 |
| Amdry 5260 | $Cr_3C_2$ 25(Ni 20Cr) | Pass | 0.0081 | 47.48 | 0.189 | 0.004 | 29.21 |
| SM 5847 | WC 10Co 4Cr | FAIL | 0.0227 | 33.26 | 0.447 | 0.0055 | 32.87 |

# Appendix 3. Implementation Assessment of ID Plasma Spray at NADEP JAX

An Implementation Assessment was carried out to evaluate the costs, benefits, technology readiness and risks of replacing ID chrome plate with plasma spray at NAEDP Jacksonville.

# Implementation Assessment

## *Replacement of Internal Diameter Hard Chrome with Plasma Spray Coatings at NADEP Jacksonville*

*Authored by:*

*Keith Legg*

*Rowan Technology Group*

**Organization: HCAT**

**Project #: SERDP PP-1151**

**Report Number: Final Implementation Assessment**

**Date: April 4, 2004**

DISTRIBUTION STATEMENT: None

ROWAN TECHNOLOGY GROUP

1590 S. Milwaukee Ave., Suite 205, Libertyville, IL 60048, USA • 847-680-9420 • Fax: 847-680-9682
Email: rowan@rowantechnology.com • www.rowantechnology.com

# ACKNOWLEDGEMENTS

We would like to thank the NADEP Jacksonville personnel who have assisted in providing the input for this report:

Daming Wang and John Quets, Praxair

Chris Dambra and Montia Nestler, Sulzer Metco

John Lamkin, NADEP Jacksonville

Ernestine Lawson, NADEP Jacksonville

Gary Whitfield, NADEP Jacksonville

Jon Deveraux, NADEP Jacksonville

Bruce Bodger, Hitemco

# EXECUTIVE SUMMARY

This report assesses the implementation of plasma spray for replacement of engineering hard chrome (EHC) plate for overhaul of internal diameters of aircraft components at NADEP Jacksonville. Technical assessment is based upon the results of SERDP Project # PP-1151 and commercial and field experience with the technology. Cost assessment is based on data obtained in prior cost benefit analyses by NADEP Jacksonville, updated by a field visit, combined with data from a Navy/Industry task force that analyzed the impact of a new OSHA PEL.

Plasma spray is a mature thermal spray technology that is already used at NADEP JAX for engine overhaul. ID plasma spray complements HVOF by coating internal (non-line-of-sight) areas that are inaccessible to HVOF. The primary applications are IDs of landing gear outer cylinders and hydraulic actuator outer cylinders. The probability of successful qualification for these applications is high. The technology is limited to IDs above 2.5" for the two primary plasma spray guns tested (the Praxair 2700 and Sulzer Metco F210), although the new Sulzer Metco F300 gun has been demonstrated to work down to 1.6" ID. The larger F100 gun can coat IDs down to 4", which encompasses >90% of all ID coated components overhauled at JAX.

Technically, ID plasma spray is not as mature as OD plasma spray. Equipment, spray methods and materials are fully commercial, while the specific spray method and material performance for IDs are now at a TRL 4 level, meaning that they are ready for validation and qualification. Plasma spray can coat IDs with the same coating materials with which HVOF can coat ODs. However, the performance of the ID material is somewhat below that of HVOF. It has lower hardness and wear resistance, lower adhesion strength and more porosity. However, the performance of ID plasma spray WC-Co is at least as good as, and probably somewhat better than EHC, with a likelihood of improved wear life and hence reduced repair frequency.

A standard Cost-Benefit Analysis using the C-MAT modelshows that the cost of ID plasma spray using the F100 gun is approximately equal to the current cost of chrome plating. Given the cost of implementation (capital, qualification and other adoption costs) this would make the technology not cost-effective unless field testing proves the technology to have better wear resistance. However, OSHA is under court order to produce a new PEL for $Cr^{6+}$, and the new PEL is expected to be close to 1$\mu$g m$^{-1}$, which is two orders of magnitude lower than the existing PEL. Should this level be adopted it is estimated by a Navy/Industry task force that the cost of chrome plated will double for the types of operations carried out at JAX. This would make the plasma spray alternative cost effective. For a complete changeover from EHC to plasma spray over 10 years, a PEL close to 1$\mu$g m$^{-1}$, and a twofold wear life improvement, we estimate that the Net Present Value (NPV) would be $2 million, with an Internal Rate of Return (IRR) of 14%, a Return on Investment (ROI) of 47%, and a Payback Period of 8 years.

However, this type of narrowly-focused Cost-Benefit Analysis measures only the cost and benefit to the depot itself, not to DoD as a whole. The true value to DoD of adopting ID Plasma Spray at JAX and other depots is not the limited

payback calculated from in the standard manner, but is seen in two more important ways:

1. **ID Plasma Spray complements HVOF, making it possible to entirely eliminate chrome plating from DoD operations.**
2. **The turnaround time for plasma spray operations is a few hours rather than the several days needed for EHC and all the required heat treatments. The result of this, together with other time-saving measures, is faster weapons turnaround to the fleet, and a higher number of combat-ready aircraft for war operations.**

# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

# 1. Introduction

Hard chrome plating has traditionally been used for rebuilding dimensions and repairing worn components. Because of its generation of large volumes of hexavalent chrome mist and of hexavalent chrome-contaminated wastewater, DoD would like to replace hard chrome plating.

In common with several other Air Force and Navy depots, NADEP Jacksonville has begun to replace chrome plating with thermal spray. Other analyses have found that approximately 65% of the workload at the NADEPs involves coating outside diameters, much (if not all) of which is likely ultimately to be replaced by high velocity oxy-fuel (HVOF) thermal spray coatings, primarily WC-Co (cobalt-cemented tungsten carbide). However, while these coatings can be used for replace chrome plate on outside diameters (ODs), they are not capable of replacing hard chrome on most internal diameters (IDs) because an HVOF gun cannot fit inside most IDs, making it possible to spray an HVOF coating onto an ID only to a depth of about one diameter.

Another thermal spray technology, plasma spray, can, however, be used inside internal diameters. This technique was developed for IDs down to 3” and evaluated under SERDP Project #PP1151. This SERDP program also evaluated a new plasma spray gun that can coat IDs as small as 1.6”.

# 2. Process/Product to be Replaced

Hard chrome plating on IDs is done in the same way as on outside diameters, using a chromic acid (hexavalent chrome) solution.

## 2.1. Description

In service many weapons system components suffer wear or corrosion. During depot maintenance cycles dimensional restoration is needed to bring them back to specification. This is usually done by hard chromium plating (up to a thickness of 0.015”), or if a more extensive build-up is required, by a combination of sulfamate nickel, often with a hard chrome overlay.

The chromium plating solution is composed of chromic acid (containing hexavalent chromium as $CrO_3$) and sulfuric acid. The process

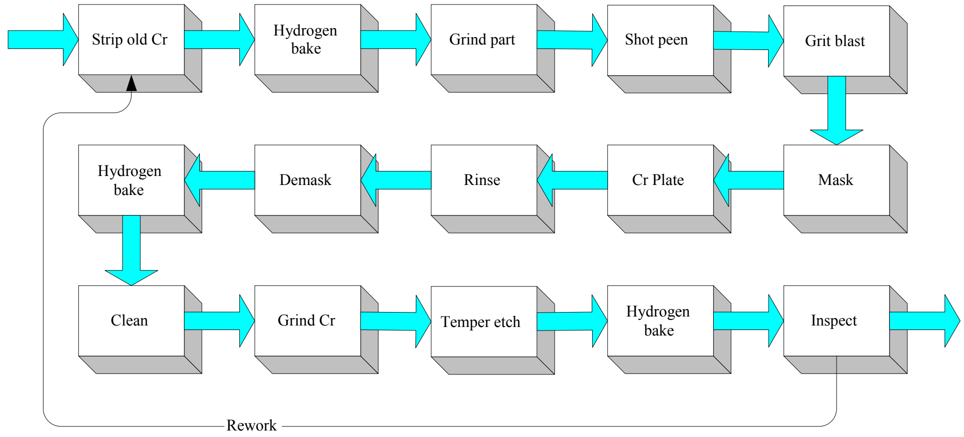



**Figure 2-1. Chrome plating simplified flow diagram (high strength steel).**

ESOH issues arise at the following points in the process:

1. Chrome strip – Electrolytic strip in sulfuric acid. Cr-contaminated waste.
2. Chrome plating – $Cr^{6+}$ mist (air emissions). $Cr^{6+}$-contaminated waste.
3. Rinse – $Cr^{6+}$-contaminated rinse water.
4. Demask – $Cr^{6+}$-contaminated maskant.
5. Grinding – Cr metal-contaminated cutting fluid, Cr dust.

Rework rates are often high, meaning that a significant number of components must go through the process more than once per cycle because of plating problems.

At any step that evolves hydrogen (stripping, plating, temper etching) any high strength steel must be hydrogen baked. Since the Cr-plating process itself is very slow (typically 0.0005" per hour), it commonly takes 24 hours, while hydrogen baking is usually specified as 23 hours at 375°F, except after temper etch inspection (for grind damage), when a 4-hour bake can be used. Thus, with masking and demasking, process time is typically 3-4 days.

## 2.2. Technical requirements

In general chrome plating has the following major requirements:

- External and internal surfaces – plating over areas defined by mask material.
- Thickness 0.003" – 0.020", as-coated, for replacement and rebuild. (Note that thin dense chrome, less than 0.001" thick, is not a depot process.)
- Hardness >700HV (although in general hardness is expected to be 800-1,000HV).
- Hydrogen baking for embrittlement-relief of high strength steels, to be done typically within 4 hours of plating.

## 2.3. Specifications

The primary DoD specification for hard chrome is MIL-STD-1501C with QQ-C-320B, but several other specifications exist as shown in Table 2-1

**Table 2-1. Hard chrome specifications[1].**

| Current Process | Application | Current Specifications |
|---|---|---|
| Hard Chromium Electro-plating | Rebuilding Worn Components<br><br>Wear-resistant Coating<br><br>Corrosion-resistant Coating | **MIL-STD-1501C**<br>**QQ-C-320B**<br>DOD-STD-2182<br>MIL-C-14538C<br>MIL-C-20218F<br>MIL-H-83282 |

# 3. New Process/Product Description

The process under evaluation to replace chrome plating of IDs is internal plasma spray. The equipment to do this is commercially available and the method is described below.

## 3.1. Equipment

Standard commercial spray units are manufactured by Praxair and Sulzer Metco. Coating material is sprayed from the bottom (thin end) of the gun either radially outwards or at an angle so as to be able to spray the end of a closed tube. Some units also permit straight-down spraying to better spray a tube end.

The depth that can be sprayed is limited by the length of the extension, with typical extensions being 12-24” (although longer units can be supplied).

Although most of the guns can physically fit inside a 1” diameter tube, the

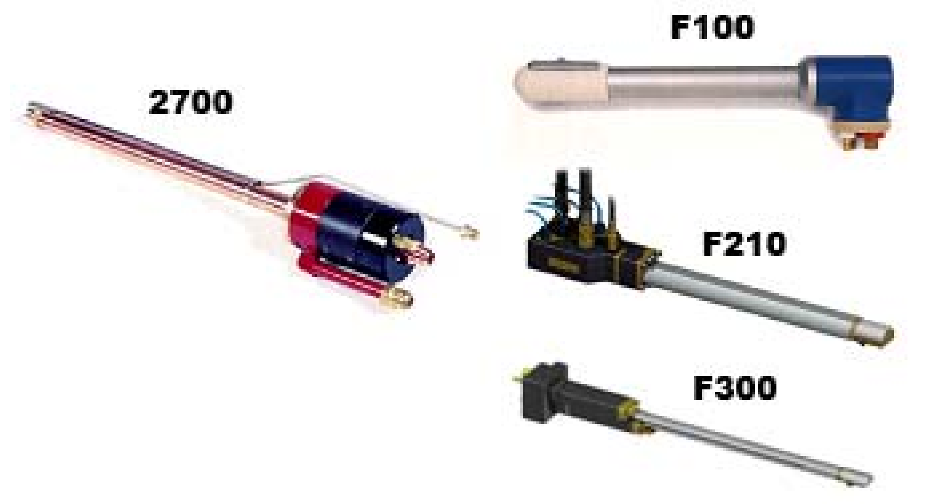



**Figure 3-1. ID plasma guns - Praxair 2700, Sulzer Metco F100, F210, F300.**

practical limit to the minimum sprayable diameter is governed by the standoff distance, i.e. the distance required between the gun exit and the wall of the tube. This distance varies with the equipment, but is usually an inch or so to give enough distance for acceleration and heating of the powder particles. This gives a minimum sprayable ID, summarized for the different guns in Table 3-1.

**Table 3-1. ID plasma spray gun specs.**

| Gun | Minimum spayable ID | Powder feed rate |
|---|---|---|
| Praxair 2700 | 2.75” | 20 gm/min |
| Sulzer Metco F100 | 4” | 40 gm/min |
| Sulzer Metco F210 | 2.75” | 20 gm/min |
| Sulzer Metco F300 | 1.6” | 20 gm/min |

## 3.2. Process Description

In the plasma spray process an arc is struck between an anode and cathode inside the spray gun and a stream of gas (Ar or Ar + $H_2$) is blown through it to create a hot gas jet. Powder is injected into the jet, where it is accelerated and melted or softened so that when it impacts on the substrate it cools rapidly to form a high quality coating of the powder material. An ID plasma spray arrangement is shown schematically in Figure 3-2.

To coat an ID the gun is moved back and forth inside the ID while rotating either

the gun or (more commonly) the component to obtain uniform deposition.

Areas that are not to be coated are masked with metal masking that is usually fabricated to fit the component and can be used many times, with grit blasting to remove excessive coating as needed.

The closed end of a tube may be coated either with the same gun or with a straight-on gun that sprays axially rather than at an angle, depending on the gun design and the size of the component.

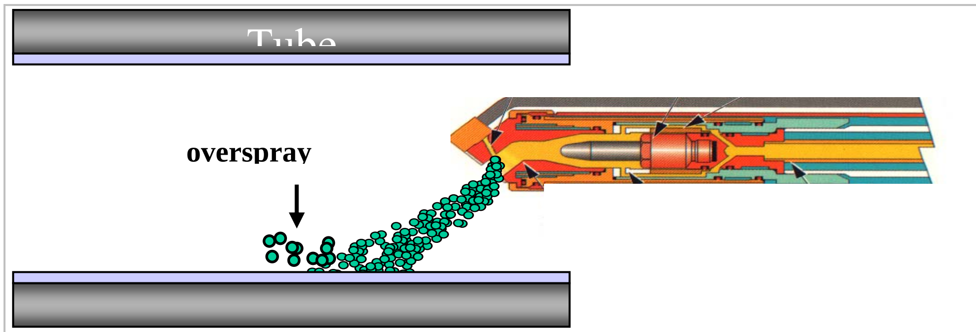



**Figure 3-2. ID plasma spray.**

The spray process flow diagram is shown in Figure 3-3. Note that this process is significantly simpler than the ID chrome plating process shown in Figure 2-1. This is primarily because it eliminates several of the masking, demasking and hydrogen baking steps. The only requirements for hydrogen baking result from the use of electrochemical processes to remove existing coatings and to check the surface for grind burns.

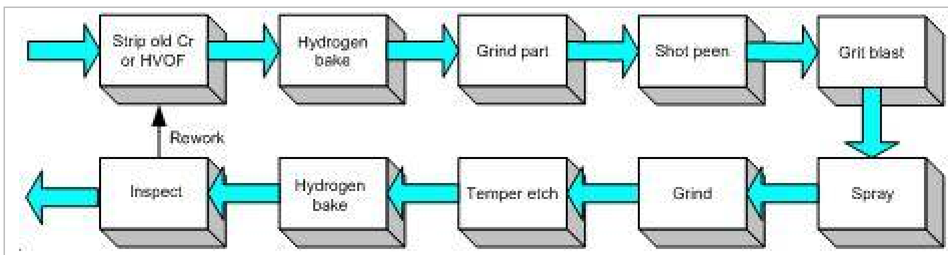



**Figure 3-3. Plasma spray flow diagram.**

## 3.3. Specifications

There are a large number of commercial specifications for plasma spray processes and powders since plasma spray is widely used in the aircraft industry. Table 3-2 shows some of the major process specifications. There are a very large number of powder specifications.

**Table 3-2. Major plasma spray specifications.**

| Specification | Description |
|---|---|
| Boeing BAC 5851 Class 1 | Plasma spray class of coatings from general thermal spray spec. |
| SAE AMS 2437 | Plasma spray coating |
| MIL-HDBK-1884 | Plasma spray coating |

The most commonly-used specification for the plasma spray process is Boeing, BAC 5851 Class 1, which covers plasma spray of materials specified in BMS10-67. (Class 2 covers HVOF and Class 3 covers Super D-gun.)

The Aerospace Materials Specification AMS2437 covers the plasma spray process, while numerous other AMS specifications cover different powders.

## 3.4. Capabilities and Advantages

**Table 3-3. Capabilities and advantages.**

| Item | Comment |
|---|---|
| **Process capabilities** | |
| Minimum ID that can be coated | 2.75" for most guns, 1.6" for F300 gun. Adequate for most actuators |
| Maximum length that can be coated | 24" standard extension length – can be extended indefinitely provided rigidity is maintained |
| Spray rate | 20 gm/min for WC-Co (F210, 2700 gun) |
| Process temperature | Can be kept below 400°F (acceptable for shot peened 4340 and similar steels) |
| **Performance** | |
| Hardness | 600 – 850HV depending on material. Meets hardness specs for EHC (700 – 1,000HV) |
| Abrasion resistance | Similar to or less than EHC |
| Thickness | Minimum 0.001", maximum >0.015". |
| Corrosion resistance | Similar to OD HVOF coatings. (With HVOF coatings test results are usually poor, but actual performance usually better than EHC) |
| Fatigue | Lower fatigue debit than EHC |
| Embrittlement | Process does not cause hydrogen embrittlement |
| **Environmental** | |
| Process location | Spray booth, robotic (no direct operator exposure) |
| Process materials | $H_2$, Ar , WC-Co or other powders |
| Waste streams | Overspray powder (low toxicity) – trapped in bag house |

The process can be applied to most components that are currently chrome plated on the ID.

While the performance of ID plasma spray coatings appears to be somewhat inferior to OD coatings, it nevertheless appears to meet or exceed the performance of hard chrome.

# 3.5. Limitations and Disadvantages

**Table 3-4. Limitations and disadvantages.**

| Item | Comment |
|---|---|
| **Process capabilities** | |
| Minimum ID that can be coated | Cannot coat inside some flight surface actuators, most pins or LVDT IDs |
| Maximum length that can be coated | Very long utility actuators are possible, but difficult. Likely to be difficult to remove overspray |
| Process temperature | Heating may require periodic halting of the process to allow the workpiece to cool |
| **Performance** | |
| Thickness | Cannot replace thin dense chrome |
| Surface roughness | Rough as-sprayed. Must be ground |
| **Environmental** | |
| | |

Some components are too small in diameter, such as the small diameter holes in actuator inner cylinders that house the LVDT (linear variable differential transformer) position sensor. While it is in principle possible to coat to any depth, long tubes (several feet) would pose problems due to lack of rigidity in the spray gun extensions and increased difficulty in removing overspray.

# 3.6. Availability and Fit with DoD Operations

## 3.6.1. OEMS

Since thermal spray (primarily plasma spray and HVOF) are heavily used in the aerospace industry, there is a large installed base of equipment and know-how, with a qualified supplier base and many OEMs having their own equipment.

While plasma spray coating is widely available commercially from aerospace-qualified suppliers, far fewer plants have the capability for ID coating. However, some aerospace-qualified companies do offer the service.

ID guns are now commercially available from both Praxair and Sulzer Metco, while the powders evaluated for ID use are also commercially available. Therefore any OEM or vendor wishing to use the technology could purchase the necessary ID gun relatively inexpensively and operate it in a standard spray booth.

## 3.6.2. Depots

The process fits well with depot maintenance activities since most depots are already use plasma spray and have all of the relevant production equipment and

know-how to carry out plasma spray ID repairs.

While they have the controllers, booths, robots, etc., few are likely to be equipped with ID spray guns. Thus, for low production volumes a depot can simply purchase the ID gun and use the existing spray booths and controllers for ID coating. For high production volumes additional complete production booths and spray systems would need to be purchased.

# 4. Gap Analysis

What will it take to bring this to full implementation? What are the technology gaps? Who needs to buy-in? What about qualification, training, maintenance?

## 4.1. Technology Status Summary

The ID plasma spray technology has been developed and tested under SERDP Project #PP1151. During the course of the SERDP program progress was made on approving the first Navy ID plasma spray coating – plasma spray Tribaloy for the ID of the CH 53 helicopter blade damper. The status of these two applications are shown in Figure 4-1. The dark lines represent the general status of ID plasma spray, while the light lines represent the status of the CH 53 blade damper application. **There are no critical gaps.** The definitions of the Technology Readiness Level ranking numbers at the top of the graph are provided in Section 10.

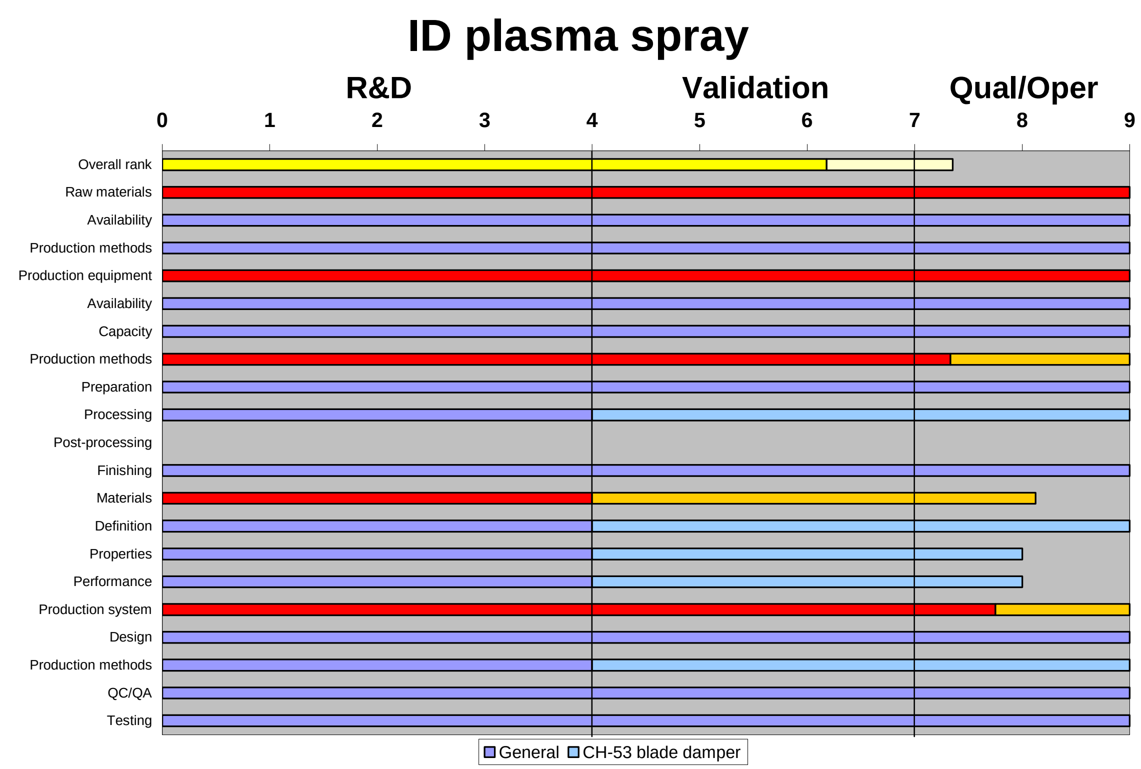



**Figure 4-1. TRL for ID plasma spray and CH-53 blade damper. (For TRL definition see 10.)**

## 4.2. Technology gaps – cost and time estimates

**The following items are sufficiently developed for production:**

- Raw materials (powders and gases) are commercially available in the proper form.
- Production equipment is commercially available at the proper scale – there are no scale-up issues.
- Basic production set up and booth design are well known and commercially available.
- During the SERDP program plasma spray ID coatings have met all technical requirements and the process is ready for depot validation.

**The following items require further development or demonstration:**

- **Materials properties** – Measurement of materials properties in a range of ID situations characteristic of actual components. This will require more extensive testing of mechanical and chemical properties.
- **Component performance** – Validation will require demonstration of the process on components, validation of the performance and QC methods

for actual component spraying, and rig or flight testing, followed by development of specifications.

- **Producibility** – The process must be demonstrated at the depot and shown to meet all the requirements for production on the shop floor with a range of typical ID coated components from the depot workload. This includes cleaning, masking, spraying, finishing and QC.

Table 4-1 provides an estimate of the costs and times required to complete the necessary tasks. The first three items in the table may be done simultaneously to provide an overall performance dataset for the technology. Following this, individual components would be qualified based on the full dataset, with additional flight testing and/or rig testing as needed. The time required for this is primarily determined by the time required to obtain flight approval and to carry out a multi-year flight test (which is usually done on an aircraft where component performance can be tracked on a regular basis. Production must be accompanied by development of specifications, NAVAIR approval, and changes to tech orders, drawings, shop travelers, etc. The cost estimate of $50,000 and two years per item is for the initial items. As the technology becomes accepted approvals will be granted with less and less testing and shorter approval times, until the approval becomes a blanket approval with exceptions for those items that may be deemed not able to be replaced, or not worth replacing because of limited remaining time in service.

## 4.3. Financial gaps

At the present time funding sources have not been identified to bring the technology to production at NADEP-JAX. We would expect that development and qualification would be done with CIP or similar funds, initially on a component-by-component basis as the best targets of opportunity are identified.

## 4.4. Qualification and approval

Production approval at NADEP JAX requires NAVAIR concurrence, which depends upon an assessment of technical risk, success in flight testing, and any additional testing and evaluation that may be required. The cost above is an estimate for spec development, approvals, and paperwork and drawing changes. Cost and time for NAVAIR approval are likely to be high and are difficult to predict for the first one or two items, but then will drop as the degree of comfort with the technology increases.

## 4.5. Probability of success

Overall the probability of successful technical qualification is high. However we have assigned a higher level of risk to the final approval process, as it could be seriously delayed if any issue arises during flight or rig testing that causes significant concern from a functionality or flight safety point of view.

**Table 4-1. Gap Analysis summary, with cost and time estimates.**

| TRL# | Gaps | Work required | Success prob | | | Est. cost | Time |
|---|---|---|---|---|---|---|---|
| | | | Low | Med | High | | years |
| 4 | Processing method | Demonstration on real components, some overspray and temperature control | | | | $50,000 | 0.5 |
| 4 | Material properties | Measurement in typical configurations | | | | $100,000 | 1 |
| 4 | Component performance | Full battery of coated materials performance tests | | | | $500,000 | 2 |
| | Component qualification | Rig and flight tests | | | | $300,000 | 3 |
| | Production approval | Spec development, approvals, TO changes, drawing changes | | | | $50,000, initial | 2 per item |

# 5. Cost/Benefit Analysis

In October 2000 NAVAIR produced a report containing a cost/benefit analysis of replacing OD hard chrome with HVOF coatings at the three Naval Aviation Depots[2]. This analysis drew on various other analyses, including a report commissioned by the JSF IPT[3] (which includes a cost analysis for ID plasma spray as a chrome replacement), but it includes corrections to the input data. Since HVOF, like plasma spray, is a thermal spray method, and since the materials to be sprayed are very similar, the basic NADEP Jacksonville cost data extracted from the report apply equally to ID plasma spray, with modifications as needed.

Keith Legg visited NADEP Jacksonville to gather additional data. Discussions revealed that the cost data have changed little (perhaps 5%) since the prior study. In addition we have corrected the cost data for thermal spray based on more recent process data from the HCAT and SERDP programs.

This cost/benefit analysis presented here uses the C-MAT (Calculation for Material Alternative Technologies) decision tool developed under SERDP funding. Note that, although it is typical for a Cost Benefit Analysis to produce a single set of values for economic payback, the nature of real-world uncertainties makes this approach unrealistic in most cases. Our analysis attempts to provide a

better picture of the possible outcome, including its major uncertainties, in order to provide a more sound basis for informed decision-making.

# 5.1. Factors affecting the Cost-benefit analysis

## 5.1.1. Process Cost-benefit issues

The costs in Table 5-1 are based on deposition rate for the Praxair 2700 tests run in the SERDP program. This table compares the cost per item and annual costs for chrome plating and for ID plasma spray using the data of Table 5-3 to Table 5-6. It is immediately apparent that ID plasma spray is a much more expensive process. Certainly, the plasma spray process avoids almost all of the environmental costs (primarily Facilities labor in the table). However, clearly, the cost of materials is much higher. In addition, the spray rate is significantly lower than for HVOF. The result of this is that the labor hours required for spraying is also much higher.

However, although the testing in the program was done with the smaller ID guns in order to determine how small an item could be sprayed, the bulk of the components at NADEP Jacksonville are large enough to be sprayed with a larger ID gun.

Three cost items primarily control the cost, as we see from Table 5-6:

1. **Spray rate with the ID gun** – i.e. powder weight sprayed per hour. Our testing was not designed to optimize spray rate. Clearly, since ID plasma guns have lower spray rates than HVOF guns, care must be taken to ensure the highest spray rate consistent with product quality and part temperature.
2. **Deposition efficiency** – This is the percentage of the material sprayed that sticks to the component. This is a function of deposition parameters, including the angle of incidence, particle temperature and velocity, and the amount of time the gun is spraying off the component. Wherever possible the gun should be normal to the surface, but in small IDs or where the end must be sprayed as well as the wall, the gun may need to be operated off-normal. In IDs, the gun usually sprays off the component only at the outer end, whereas in most OD situations it sprays off at both ends.

3. **Set-up efficiency** – This is the time required to mask the components and set up each spray run. This cost can be minimized by having hard masks and well-defined set-ups that require minimal operator adjustment. In spray booths it is quite common for the operator to set up the parts individually in the booth between runs. Efficient spraying, however, demands a more high-production-oriented workflow in which most of the set-up is done outside the booth while spraying the previous item, which would usually require two spray tables instead of the standard one.

In the SERDP program depositions were done with both Sulzer Metco F100,

**Table 5-1. Processing cost comparison – EHC vs. F100 gun ID plasma spray.**

| | EHC | | | | Plasma spray | |
|---|---|---|---|---|---|---|
| Cost source | Per aircraft | | Per year | | Per aircraft | Per year |
| Direct production labor | $ 10,038 | $/item | | | $ 6,887 | $ - |
| Indirect production labor | $ 72 | 0.72% | of direct | | $ 50 | $ - |
| Direct materials | $ 5,761 | $/item | | | $ 13,863 | $ - |
| Indirect materials | $ 100 | 1.74% | of direct | | $ 241 | $ - |
| Haz waste disposal | $ 1,770 | $/item | | | $ - | $ - |
| Utility (electricity) | $ 20 | $/item | $ 20,396 | | $ 71 | $ - |
| Indirect labor (facilities labor) | | | $ 18,226 | $/yr | $ - | $ - |
| Annual air permit fee | | | $ 200 | $/yr | $ - | $ 200 |
| Haz waste sampling | | | $ 200 | $/yr | $ - | $ - |
| Wastewater treatment | $ 2,659 | | | $/yr | $ - | $ - |
| **Total annual** | **$ 20,420** | **$/item** | **$ 18,626** | **$/yr** | **$ 21,112** | **$ 200** |

F210 and F300 guns, and the Praxair 2700 gun. The F210 and 2700 guns are meant for diameters of about 3” and above, and their performance is essentially similar. The F300 is smaller, with a lower deposition rate, and is designed for smaller diameters. For most ID applications at NADEP Jacksonville the large F100 gun would be far more cost-effective because it has approximately twice the deposition rate. Table 5-2 compares the costs of spraying with the larger and midsize guns. Clearly, the cost difference is very large, and the larger gun is the only way that ID plasma spray could begin to become cost effective.

**Table 5-2. Comparison of plasma spray cost with different ID guns.**

| Cost source | F210, 2700 gun Per aircraft | F210, 2700 gun Per year | F100 gun Per aircraft | F100 gun Per year |
|---|---|---|---|---|
| Direct production labor | $ 19,629 | $ - | $ 6,887 | $ - |
| Indirect production labor | $ 141 | $ - | $ 50 | $ - |
| Direct materials | $ 20,794 | $ - | $ 13,863 | $ - |
| Indirect materials | $ 362 | $ - | $ 241 | $ - |
| Haz waste disposal | $ - | $ - | $ - | $ - |
| Utility (electricity) | $ 128 | $ - | $ 71 | $ - |
| Indirect labor (facilities labor) | $ - | $ - | $ - | $ - |
| Annual air permit fee | $ - | $ 200 | $ - | $ 200 |
| Haz waste sampling | $ - | $ - | $ - | $ - |
| Wastewater treatment | $ - | $ - | $ - | $ - |
| **Total annual** | **$ 41,055** | **$ 200** | **$ 21,112** | **$ 200** |

Even with the larger ID plasma spray gun the per-item cost is about the same as that of hard chrome, as we see in Table 5-1.

At an overhaul rate of 20 aircraft per year (35% of the total in Table 5-3) the annual cost for chrome plate is $427,026, while the annual plasma spray cost with the larger gun is estimated at $422,440. Thus the annual processing costs are essentially the same. Given the capital expenditure to install the plasma spray and the cost of qualifying plasma spray coatings, changing TOs, etc., it is clear that, even with the larger ID gun, processing cost alone does not provide a financial justification for a change.

## 5.1.2. Performance Cost-benefit issues

### 5.1.2.1. Service performance

Because of their higher hardness HVOF WC-Co coatings are known to improve service performance over that of EHC in most sliding wear and hydraulic applications, leading to a much lower frequency of overhaul (typically a factor of three or more), which greatly reduces life-cycle cost. The plasma spray coatings are not generally greatly different in hardness from chrome plate, except for WC-12Co. For most plasma sprays, therefore, we expect no service life enhancement. WC-C12Co is harder than the chrome plate average and shows about a factor of two reduction in erosion rate. It does not show any improvement over hard chrome in ring-on-block sliding wear tests, but those tests represented only wear against hard metallic materials, not wear against soft bushings or Teflon or elastomeric seals. In normal hydraulic and landing gear applications we expect the wear to be more strongly governed by the hardness, as we have found with HVOF coatings, provided the surface is properly superfinished.

Thus we expect that for most plasma spray materials the wear rate will be similar to that of hard chrome. Only WC-12Co is expected to have a lower wear rate, with a wear life that might be about twice that of hard chrome.

#### 5.1.2.2. Service failures

There is no evidence that plasma spray will reduce service failures. The plasma spray process does not cause embrittlement, as chrome plating does. Thus it is possible that service failures might be reduced through the elimination of any hydrogen embrittlement failures that may be due to inadequate hydrogen baking after chrome plating. However, hydrogen embrittlement failure does not appear to be an issue with this type of component.

### 5.1.3. Development and implementation cost issues

The costs of implementation are highly uncertain as they depend on the number of applications, the degree of similarity between them, and the level of testing required to obtain NAVAIR approval. The costs we have assumed (Table 5-5) are based on what we believe are reasonable average costs for qualifying and recertifying a number of components over a period of several years. These costs have been assigned a 50% accuracy level, indicating this high level of uncertainty. These costs are high at the outset but drop with time as more data and operational experience are acquired.

### 5.1.4. Environmental cost issues

The environmental costs of chrome plating are likely to change over the coming five years as a result of a new OSHA PEL. OSHA has been considering for some years lowering the PEL for worker exposure to hexavalent chrome, but the matter has been delayed by opposition from the finishing industry. However, OSHA is under court order to propose a new standard, as described in a briefing presented to the American Electroplaters and Surface Finishers Society (AESF)[4]. Under the court order the new standard is scheduled to be published in the Federal Register in October 2004 and to be finalized in January 2006. The new PEL is expected to mandate a two order of magnitude reduction from the current 100 $\mu gm^{-3}$ for chromic acid mist to 1 $\mu gm^{-3}$, with an action level of 0.5 $\mu gm^{-3}$.

A Navy/industry task group[5] has evaluated the potential costs to the Navy of various PEL levels, based on all manufacturing and maintenance operations that can produce $Cr^{6+}$ emissions, including plating, grinding and welding. Their analysis included cost estimates based on industry and Navy depot averages and included specific numbers for exposed workers at the NADEPS, including NADEP Jacksonville. We have extracted from the report the plating cost information relevant to NADEP Jacksonville. These numbers are only very approximate since the study was hurried and used rule-of-thumb cost evaluations, applying averages to each location. The costing methodology used is not clear, and it may count some workers more than once. Nevertheless this document does provide a rough estimate of the potential cost of a lower OSHA PEL.

This task group report considered the costs of a PEL set at the level of 0.5, 5 and 10 $\mu gm^{-3}$, rather than what is now believed to be the probable value of 1 $\mu gm^{-3}$. However, from their standard deviations 92% of those workers exposed at a level of 0.5 would also be exposed at a level of 1 $\mu gm^{-3}$. The PEL would affect both platers and grinders. Some grinders would be involved in grinding welds and some chrome plate, but the number involved in chrome plate grinding can be deduced by subtracting those involved in weld grinding (presumably the same people as the welders themselves). Thus it is possible to estimate the total

number of exposed workers involved in plating and grinding of plated parts.

The study estimated that at a typical Naval base the one-time cost of a PEL of 0.5 $\mu gm^{-3}$ would be $1,647 per affected worker, while the annual cost (including loss of efficiency) would be $3,444 per worker.

Using 92% of the numbers of workers affected by plating and grinding of plated parts at Jacksonville (405 affected by grinding operations and 100 by plating, for a total of 505, according to the study2) and then taking 35% of this to reflect the contribution from the ID plating load only, we find the following approximate costs attributable to ID chrome plating at ID EHC at NADEP-Jacksonville:

- One-time cost $267,750
- Annual cost $560,000

In the cost calculations, we have assigned a 50% error to this cost. While this is only a very rough estimate, it does provide a means of assigning what should be a reasonably realistic cost for chrome plating operations.

## 5.2. Inputs and assumptions

Table 5-3 and Table 5-4 list the cost inputs to the model for the current chrome plating process. **Note: In each table an Item is a complete aircraft, from which a number of components must be coated.** Costs are based on the average aircraft overhaul numbers from NADEP Jacksonville.

NADEP JAX is beginning to replace EHC with HVOF on ODs, which are 65% of the depot workload. ID surfaces constitute the remaining 35% of the workload, and cannot be HVOF sprayed. Obviously this means that on average 35% of the chrome plating done for each aircraft is ID chrome, not that 35% of the aircraft are entirely ID coated and 65% are OD coated. But for the purpose of the calculation it is easier to treat the problem in the latter manner since it makes no mathematical difference.

2 Note: This is not necessarily only the number of grinders and platers, but may include any worker affected by those operations.

**Table 5-3. Data used in NADEP Jacksonville analysis – general process data.**

| Cost item | Quantity | Unit | Source* |
|---|---|---|---|
| **Work volume** | | | |
| # Aircraft serviced per year | 56 | | Table 1.1-2 |
| Area plated per year | 19,684 | sq ft | Table 1.1-2 |
| Average area plated/aircraft | 351.50 | sq ft | derived |
| Aircraft in the fleet | 466 | | Table p9 |
| Average overhaul cycle | 8.32 | years | derived |
| | | | |
| **Rates** | | | |
| Labor rate - direct | $ 51.43 | $ per hr | Table 1.1-2 |
| Labor rate - indirect | $ 0.37 | $ per hr | Table 1.1-4 |
| Material - indirect | $ 0.05 | $/lb | Table 1.1-6 |
| Energy cost | $ 0.05 | $/kWh | Table 1.1-6 |
| Inflation rate** | 10% | | Table 1.1-6 |
| Discount rate | 4.02% | | Table 1.1-6 |
| Depreciable life of equipment | 12.00 | yr | Table 1.1-6 |
| Salvage value | 10% | | Table 1.1-6 |
| | | | |
| **Hazardous waste** | | | |
| **TRI materials - current** | | | |
| Materials | 98,358 | lb/yr | Table 1.1-1b |
| Chemicals | 13,209 | lb/yr | Table 1.1-1b |
| Waste disposal | 75,074 | lb/yr | Table 1.1-1b |

**Reference 2*

***This was used in tables – calculation, however, assumed no inflation.*

**Table 5-4. Data used in NADEP Jacksonville analysis – OD + ID EHC.**

| Cost item | Quantity | Unit | Ann fixed | Unit |
|---|---|---|---|---|
| **Hard chrome** | | | | |
| **Annual** | | | | |
| Direct production labor | $ 562,101 | $/yr | | |
| Indirect production labor | $ 4,033 | $/yr | | |
| Direct materials | $ 322,626 | $/yr | | |
| Indirect materials | $ 5,607 | $/yr | | |
| Haz waste disposal | $ 99,098 | $/yr | | |
| Utility (electricity) | $ 21,523 | $/yr | | |
| Indirect labor (facilities labor) | $ 18,226 | $/yr | | |
| Annual air permit fee | $ 200 | $/yr | | |
| Haz waste sampling | $ 200 | $/yr | | |
| Wastewater treatment | $ 148,924 | $/yr | | |
| Total annual | $ 1,182,538 | $/yr | | |
| **Per item** | | | | |
| Direct production labor | $ 10,038 | $/item | | |
| Indirect production labor | $ 72 | 0.72% | of direct | |
| Direct materials | $ 5,761 | $/item | | |
| Indirect materials | $ 100 | 1.74% | of direct | |
| Haz waste disposal | $ 1,770 | $/item | | |
| Utility (electricity) | $ 20 | $/item | $ 20,396 | |
| Indirect labor (facilities labor) | | | $ 18,226 | $/yr |
| Annual air permit fee | | | $ 200 | $/yr |
| Haz waste sampling | | | $ 200 | $/yr |
| Wastewater treatment | $ 2,659 | | | $/yr |
| Total annual | $ 20,420 | $/item | $ 18,626 | $/yr |
| **EHC Breakdown** | | | | |
| Direct labor | 195 | hrs/item | | |
| Haz waste generated | 75,074 | lb/yr | | |
| Haz waste per item | 1,341 | lb/item | | |
| Waste disposal | $ 1.32 | $/lb | | |
| Rinsewater use | 135,386 | gal/yr | | |
| Rinsewater /item | 2,417.61 | gal/item | | |
| Wastewater treatment | $ 1.10 | $/gal | | |
| Wastewater treatment cost | $ 2,659 | $/item | | |
| Plating power | 1.08 | kW-h/sq ft | | |
| Plating power | 380 | kW-h/item | | |
| Scrubber power | 17.99 | kW-h/sq ft | | |
| Scrubber power | 6,323 | kW-h/item | | |
| Tank heater power | 1.56 | kW-h/sq ft | | |
| Tank heater power | 548 | kW-h/item | | |
| Haz waste mgnt labor | 1 | hr/420 lbs | | |
| Haz waste mgnt labor | 0.0024 | hrs/lb | | |
| Haz waste mgnt labor cost | $ 178.75 | $/yr | | |
| Hazmat tracking for TRI | 200 | hrs/year | | |
| Hazmat tracking for TRI | $ 10,286 | $/yr | | |
| Air quality reporting | 137 | hrs/yr | | |
| Air quality reporting | $ 7,046 | $/yr | | |
| Other waste mgnt labor | $ 715.34 | $/yr | | |

**Table 5-5. Data used in Rowan analysis – Plasma spray capital and implementation costs.**

| **Plasma spray capital cost** | |
|---|---|
| Plasma spray system | $65,000 |
| Console | |
| ID gun | |
| Power supply | |
| High freq unit | |
| Powder feeder | |
| Cables, etc | |
| Dust collector | $25,000 |
| Spray booth | $15,000 |
| Robot + lathe | $95,000 |
| Robot ceiling mount | $20,000 |
| Heat exchanger | $15,000 |
| Grit blaster | $15,000 |
| Hard masking, etc | $25,000 |
| Engineering | $50,000 |
| Installation* | $265,000 |
| **Total** | **$525,000** |
| **Plasma spray implementation cost** | |
| Materials qualification testing | $450,000 |
| Process training | $10,000 |
| Component recertification | $420,000 |
| **Total** | **$880,000** |
| **Discount rate**<br>**Inflation rate** | **4%**<br>**0%** |

* Highly variable, depending on detailed engineering and location

**Table 5-6. Data used in Rowan analysis – Plasma Spray running cost (SM F100 gun), 35% EHC workload.**

| Cost item | Quantity | Unit |
|---|---|---|
| % workload replaced - OD | 35% | |
| Avg overhauls/yr | 19.6 | |
| Annual coated area | 6,889 | sq ft |
| Deposit efficiency | 75% | |
| Weight sprayed for 0.010" | 1.01 | lb/sq ft |
| Coverage rate for 0.010" | 5.25 | sq ft/hr |
| Powder sprayed/item | 354 | lb/item |
| Spray time per item | 67 | hours/item |
| Set-up, mask, demask | 67 | hours/item |
| Spray hours per year | 1,312 | hrs/year |
| Total booth hours/year | 2,625 | hrs/year |
| Powder cost/item | $ 13,435 | $/item |
| Argon | 34.60 | cu ft/lb powder |
| Argon | 12,233 | cu ft/item |
| Argon | $ 367 | $/item |
| Hydrogen | 8.67 | cu ft/lb powder |
| Hydrogen | 3,065 | cu ft/item |
| Hydrogen | $ 61.30 | $/item |
| Total materials/item | $ 13,863 | $/item |
| Gun power | 20 | kW |
| Utilities/item | $ 71 | $/item |
| | | |
| Plasma spray annual | | |
| Direct production labor | $ 134,993 | |
| Indirect production labor | $ 972 | |
| Direct materials | $ 271,714 | |
| Indirect materials | $ 4,728 | |
| Haz waste disposal | $ - | |
| Utility (electricity) | $ 1,391 | |
| Indirect labor (facilities labor) | | |
| Annual air permit fee | | $ 200 |
| Haz waste sampling | | $ - |
| Wastewater treatment | | $ - |
| Total annual | $ 413,799 | $ 200 |
| | | |
| Plasma spray per item | | |
| Direct production labor | $ 6,887 | |
| Indirect production labor | $ 50 | |
| Direct materials | $ 13,863 | |
| Indirect materials | $ 241 | |
| Haz waste disposal | | |
| Utility (electricity) | $ 71 | |
| Indirect labor (facilities labor) | | |
| Annual air permit fee | | $ 200 |
| Haz waste sampling | | |
| Wastewater treatment | | |
| Total per item | $ 21,112 | $ 200 |

## 5.3. Scenarios

### 5.3.1. Baseline Scenario

The Baseline Scenario is based upon the costs detailed in Table 5-3 and Table 5-4. The cost for ID chrome plating was taken as the cost/item multiplied by the number of items equal to 35% of the total workload, plus 35% of the annual fixed cost. As we have noted above, treating the ID workload as 19.6 aircraft (which is of course physically meaningless) is mathematically equivalent to the ID workload being 35% of 56 aircraft.

### 5.3.2. Implementation Scenarios

The costs and benefits are a function of a number of variables, including:

1. At what level the new OSHA PEL is set, and the true cost of meeting that level (see Section 5.1.4 above).
2. Whether plasma spray has a different wear rate, and hence a different service life (see Section 5.1.2.1 above).
3. Which plasma spray gun is used, since different guns have different spray rates (see Table 5-1 and Table 5-2).
4. The capital cost of installation. Note that we have assumed that an additional spray booth will be needed (Table 5-5), although until the workload is high enough it may be possible to use an existing booth and plasma spray equipment, adding only an ID gun.
5. The amount of testing, and hence the cost, of developing and qualifying component repairs.
6. In what way the process is implemented. For example one could implement it
   - All at once on all IDs
   - On all IDs over a period of time
   - On only some weapons systems or components.

We have not considered all of these scenarios, but have modeled the following:

1. Process cost comparisons (ignoring capital and implementation costs) for high rate (F100) and low rate (F210 and 2700) ID guns.
2. Immediate changeover, including capital and implementation costs for both types of gun.
3. More realistic 10 year changeover, using the F100 gun.

In each case we have considered the effects of both a strict new OSHA PEL of $1 \mu g\ m^{-1}$ and possible doubling of the service life through lower coating wear.

## 5.4. Cost-benefit evaluation

The outcome of the cost analysis depends on the cost of spraying (which is a function of the spray equipment used) and on uncertain factors such as the

service performance of the thermal spray coatings and how the OSHA PEL is changed over the coming few years.

In the SERDP ID plasma spray program the small F210 from Sulzer Metco and the 2700 gun from Praxair were the primary equipment tested, with some tests using the larger Sulzer Metco F100 and the smaller Sulzer Metco F300 guns.

Because of the uncertainties in overhaul rates, given today's operational conditions, the following analyses all assume possible 30% fluctuations in overhaul rate.

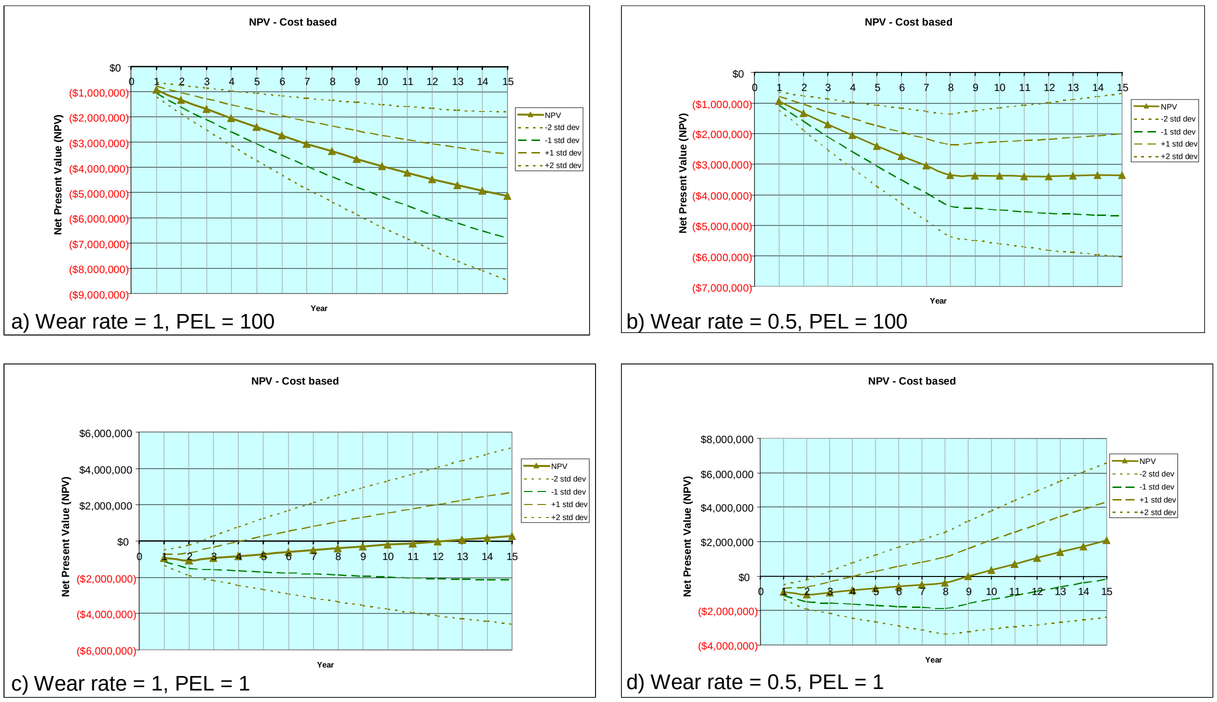
We have used a 4% discount rate and zero inflation in our cost calculations.

### 5.4.1. Simple cost comparisons

It is instructive to carry out simple cost comparisons to provide a good understanding of the various cost factors. Figure 5-1 shows some very simple cost comparisons based on an immediate changeover of all ID chrome plating at Jacksonville to ID thermal spray. These models simply compare the total costs of using plasma spray in place of hard chrome. They have the advantage of showing clearly the effects of different costs on the payback, making it easier to understand the significance of the realistic scenario shown in Section 5.4.3.

The graphs are simple costings assuming no inflation. For simplicity the Net Present Value is plotted as a function of the number of years over which it is taken. This provides an idea of how payback occurs. Payback occurs when the graph crosses the zero axis. Negative slope on the NPV implies that the annual cost of the plasma spray process is higher than EHC, while positive slope shows it to be lower.

## Small ID gun (F210, 2700)




## Large ID gun (F100)

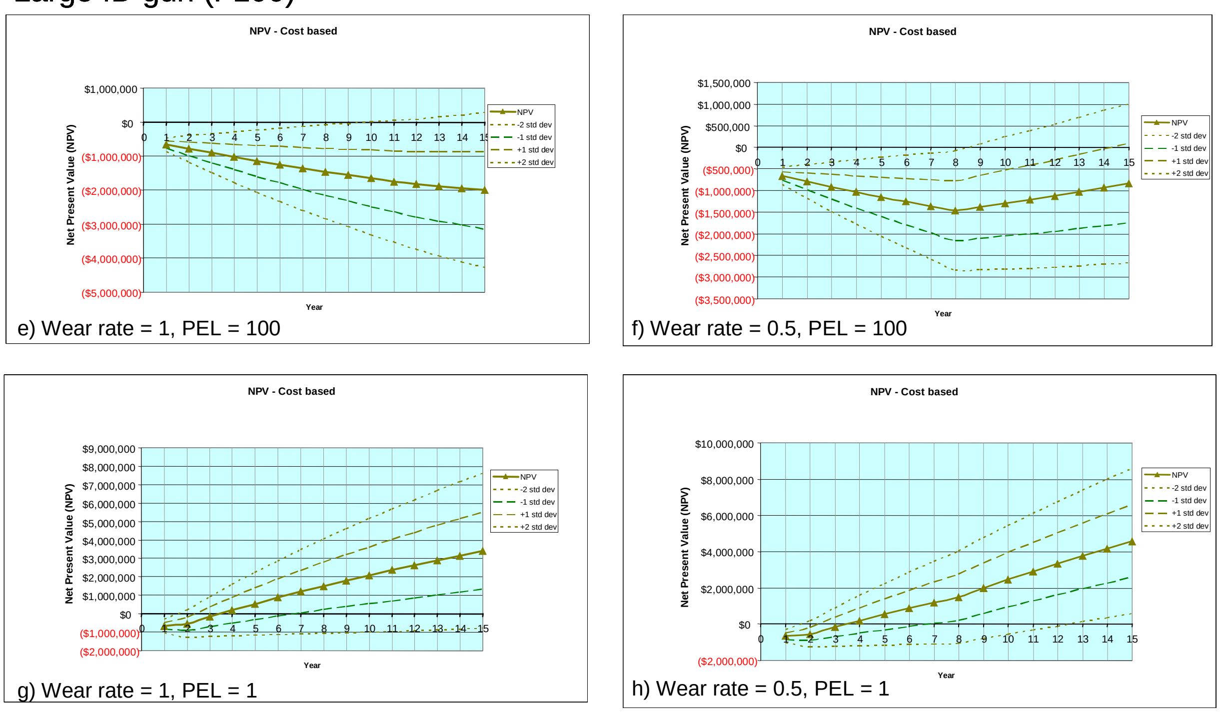



**Figure 5-1. Simple NPV calculations for low and high wear rate, low and high PEL. Small ID gun (top) and large ID gun (bottom).**

If the entire ID production were to be done immediately using a small ID gun, the cost per unit would be about twice that of chrome plate, with the result that the process could not be cost-effective (Figure 5-1a).

If the plasma spray WC-Co coating proves to have a twofold improvement in performance in service, as indicated by abrasive wear data, then this will double the overhaul cycle, halving the number of components to be serviced once the depot has replaced the ID plating on all of the existing items. This reduction in outlays balances the higher unit cost. The result is shown in Figure 5-1b. Clearly, this eventually makes plasma spray essentially the same cost, but does not pay back the total investment.

If the expected low OSHA PEL is enacted, this will raise the cost of chrome plating by $28,000 per aircraft, if the Navy/industry Taskforce cost analysis is correct (Section 5.1.4). This has the effect of more than doubling the cost of ID chrome plating. However, given the large uncertainty in this cost, as indicated by the dotted 1σ and 2σ lines, the NPV could vary widely, from highly positive to highly negative (Figure 5-1c). This occurs since the cost of the PEL is a major cost factor

The only scenario under which the smaller gun is likely to be cost-effective is when both the wear performance is better than that of EHC and the PEL is lowered (Figure 5-1d), and even under these conditions the payback is likely to be 9 years (although it could be much shorter or longer depending on the exact cost of the PEL and overhaul volumes).

The F100 gun, which is capable of higher deposition rates, will still be able to coat most of the ID components. Using this gun changes the economics considerably. Although, for equivalent performance and no change in the PEL, the plasma spray cost still generally exceeds that for EHC (Figure 5-1e and f), payback will occur in 2-5 years if the PEL is reduced (Figure 5-1g and h).

This simple analysis clearly shows that adoption of the larger gun for all spray jobs where it can be used is essential for achieving a cost-effective changeover. Including realistic adoption costs and changeover schedules shows that even a less expensive new technology will be more costly than one would anticipate from these simple direct cost models, showing the importance of using the simple models to identify critical cost issues at the outset. A more realistic model is given in Section 5.4.3 that is based on the use of the larger gun, since we have established it to be essential.

### 5.4.2. Cost variances – immediate changeover

The graphs in the previous section show lines for one and two standard deviations, which are based on expected accuracies in the input variables, especially assuming a 30% accuracy (2 sigma) for the work volume and a 50% accuracy for lower PEL cost. Clearly, these two quantities are major unknowns, i.e.:

1. Whether or not a plasma spray coating will be found to reduce wear in parts in service. Assume a conservative 33% probability that this will be found to be the case.
2. Whether or not the new OSHA PEL will be adopted. Assume a 50% probability for this, based on the expectations of AESF.

Based on this we can predict the probability of different NPVs.

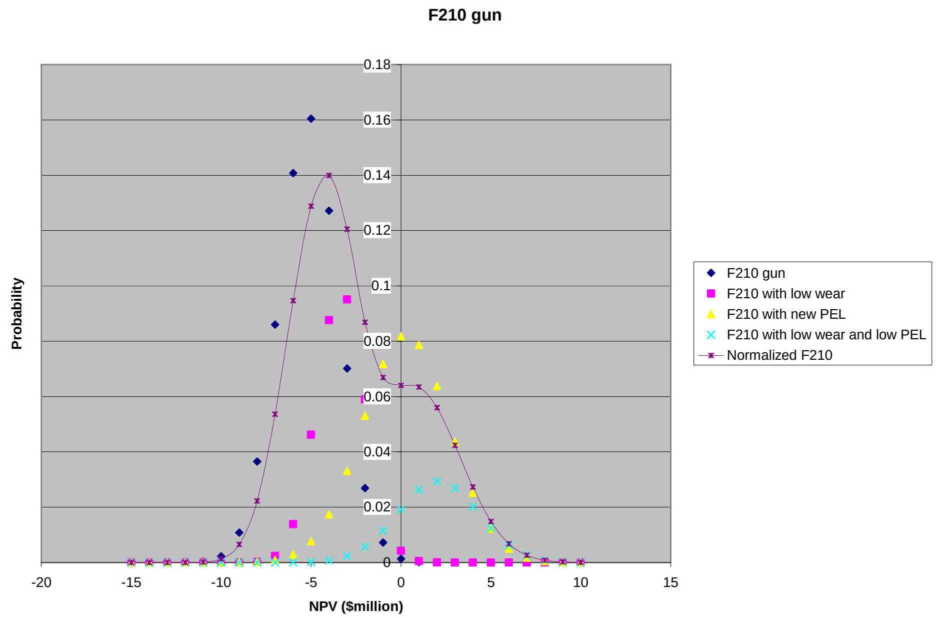



**Figure 5-2. Probability distribution for 15-year NPV, assuming use of the smaller, F210 or similar plasma gun.**

From Figure 5-2, if the smaller plasma spray gun is used there is a 70% probability that a changeover would have a *net cost* rather than a *net saving*. This is because the cost of using the small gun is very high and can only be balanced by the savings resulting from improved performance and avoidance of large costs associated with a lower OSHA PEL.

However, if the larger plasma gun is used the probability is about equal for a net cost or net saving (Figure 5-3), although the magnitude of the saving is likely to be somewhat higher than the potential loss. This is because either better performance or a lower PEL are required to make plasma spray cost-effective on a pure process and performance cost basis (i.e. excluding adoption cost).

Clearly this is not an overwhelming cost reason for using plasma spray. It shows that it would be valuable to lower the financial risk as discussed in Section 5.5, although considerations other than pure cost could also be important, as discussed in Section 6.

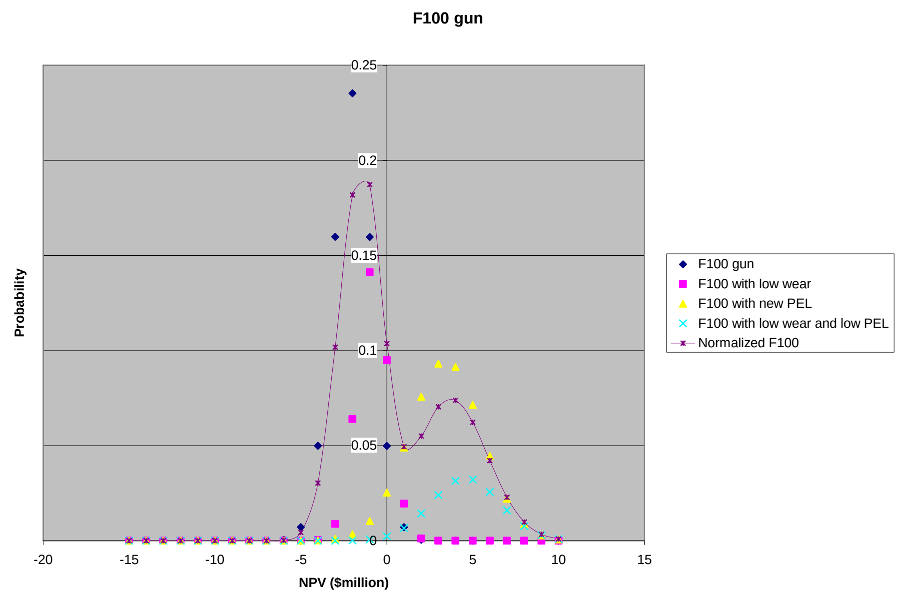



**Figure 5-3. Probability distribution for15-year NPV, assuming use of the larger F100 or similar plasma gun.**

### 5.4.3. Realistic scenario – F100 high rate spray gun with 10 year adoption

In reality, of course, it will take some time to change from ID EHC to ID plasma spray. Table 7-1 and Figure 5-4 to Figure 5-8 show the results of a changeover that takes place over a period of 10 years. The model assumes:

- An F-100 plasma spray gun can be used for all IDs
- The new OSHA PEL creates the costs estimated by the Navy/ Industry Task Force[5]
- The changeover takes place over a period of 10 years beginning in Year 3

**Table 5-7. 15-year financial results for F100 gun with OSHA PEL of 1μgm$^{-3}$ and improved wear performance. Assumes 10 year changeover.**

| | -2 sigma | Value | +2 sigma |
|---|---|---|---|
| NPV | ($2,588,124) | $1,321,544 | $5,231,211 |
| IRR | | 9% | 26% |
| ROI | 24% | 42% | 61% |
| Payback period | >15 years | 10.5 | 3.7 |

Note the following:

- Overall the results are positive if, as this model assumes, the new OSHA

PEL raises chrome plating costs as expected and plasma spray performs better than EHC. However, given the accuracy with which the costs can be estimated, there is a wide range of potential paybacks and time horizon that could well be more than 10 years. Cost is not the only consideration since a quicker turnaround can contribute to battle readiness and warfighting capability (see Section 6).

- Table 7-1 shows that at the -2σ level (worst case) the NPV is negative and the payback period falls well beyond 15 years. However, the ROI is positive since ROI is defined as the ratio of cash flow to cash invested, and cash flow is positive at 15 years – i.e. plasma spray is less expensive than EHC but the initial costs have not yet been paid back.
- Unlike the other graphs, the graph of Figure 5-4 does not show NPV vs time, but shows how NPV changes as a function of the time span from the present *over which it is measured*. Thus taking NPV over the early years of an investment tends to make it negative, while over a longer time horizon it becomes positive.
- The times at which the Cumulative Cost of Figure 5-8 cross the zero cost axis define the payback periods of Table 7-1.
- Figure 5-6 shows only positive IRR since this quantity is meaningless for negative cash flows.

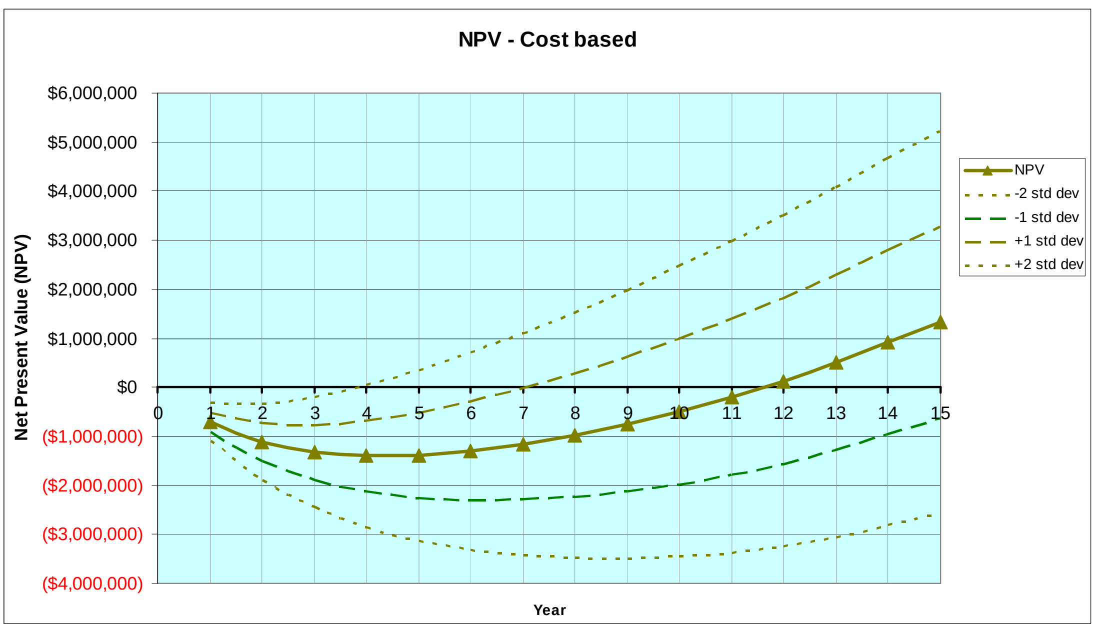



**Figure 5-4. NPV as a function of years over which it is taken, for F100 gun with OSHA PEL of 1μgm$^{-3}$ and improved wear performance. Assumes 10 year changeover.**

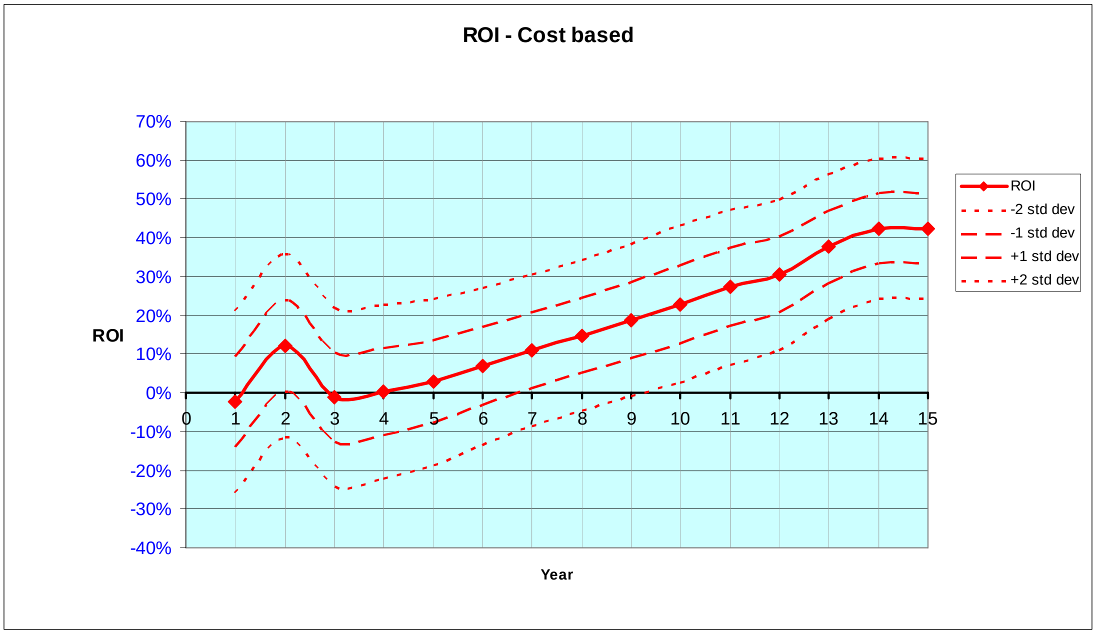



**Figure 5-5. Annual ROI as a function of time for conditions of Figure 5-4 - OSHA PEL of 1μgm$^{-3}$ and improved wear performance. Assumes 10 year changeover.**

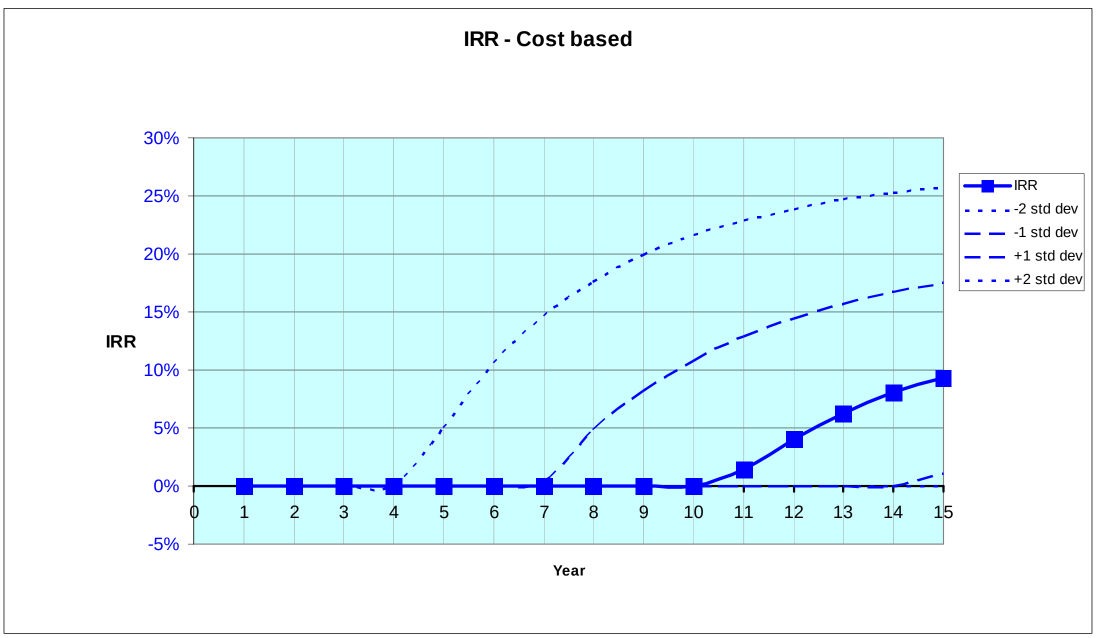



**Figure 5-6. IRR as a function of time for conditions of Figure 5-4 - OSHA PEL of 1μgm$^{-3}$ and improved wear performance. Assumes 10 year changeover.**

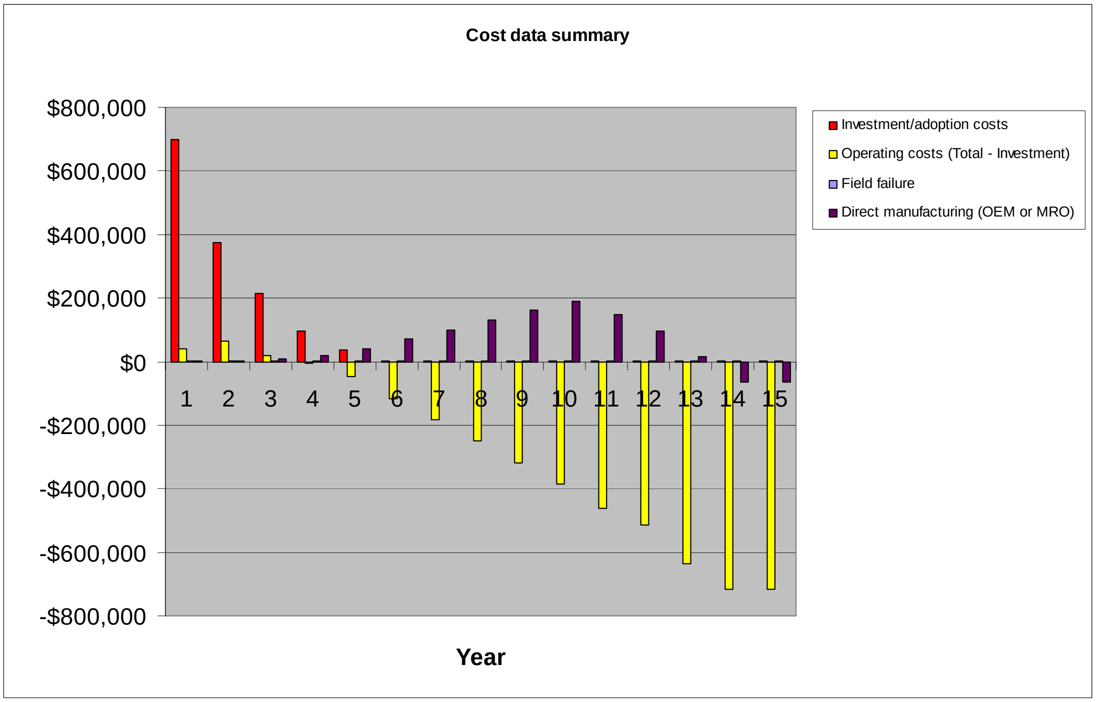



**Figure 5-7. Primary cost data over time for conditions of Figure 5-4 - OSHA PEL of 1μgm$^{-3}$ and improved wear performance. Assumes 10 year changeover.**

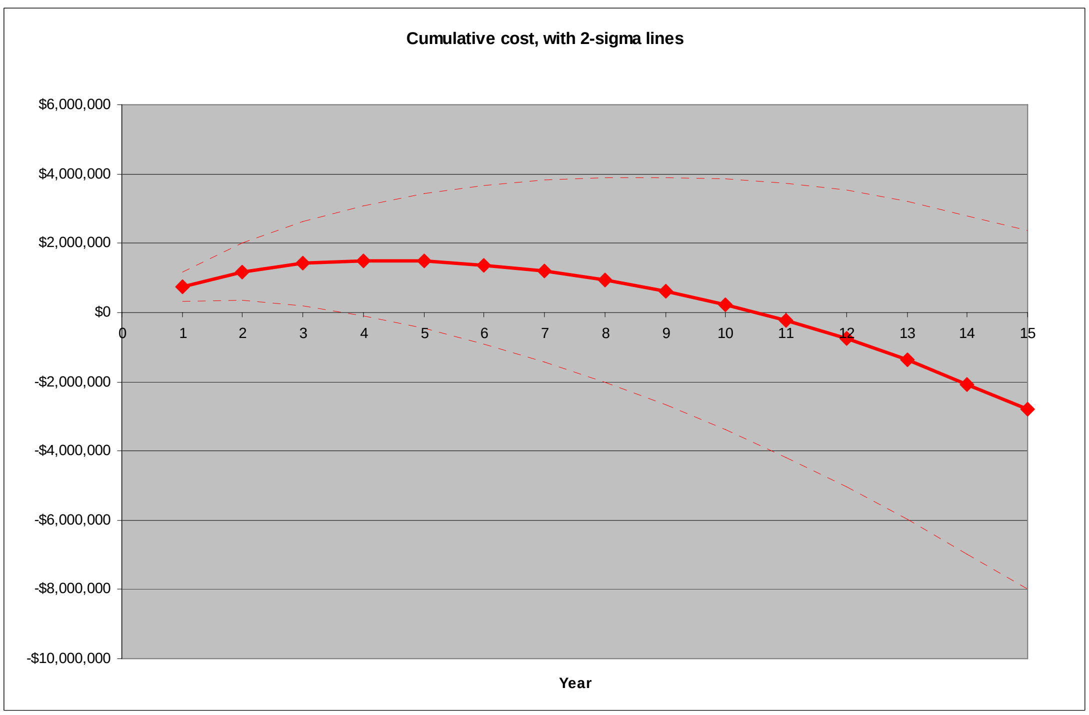



**Figure 5-8. Cumulative cost over time for conditions of Figure 5-4 - OSHA PEL of 1μgm$^{-3}$ and improved wear performance. Assumes 10 year changeover**

## 5.5. Optimum method of adoption

The analysis clearly shows that maximum spray rate is essential for the method to be cost-effective. Thus the equipment purchased should be an F100 or similar gun rather than the smaller F210 or 2700 guns. This gun can coat down to a minimum diameter of 4", which covers >90% of the ID plated components currently overhauled at NADEP JAX. A smaller gun could be obtained for the remaining components (as Table 5-5 shows, the gun cost is relatively small). As noted in Table 5-6, spraying with this gun would require about 1,300 spray hours per year and about 2,600 booth hours (which include al the set-up, cool time, etc.). At full capacity the workload should be able to be done in a single booth with two shift operation, even allowing for booth maintenance down-time.

Clearly, given the time required for process validation and testing, it is not realistic to make an immediate changeover – nor is it necessarily desirable given the uncertainties in performance and potential chrome cost. The easiest and lowest risk method of adoption will be to install the gun in an existing plasma spray booth, which will only require the ID gun itself and the hard masking needed for the initial components. Only when the technology has proved reliable and cost-effective and enough components have been approved, would it then be moved to an ID-dedicated booth.

As we have discussed in Section 5.4.2 the cost-effectiveness of the alternative is strongly dependent on the level of the new OSHA PEL and the true cost for NADEP JAX to meet it. In addition it depends strongly on the performance of the new coating. Both of these are discussed under Risks in Section 7, where we also discuss how best to minimize technical and business risk.

## 5.6. Example component

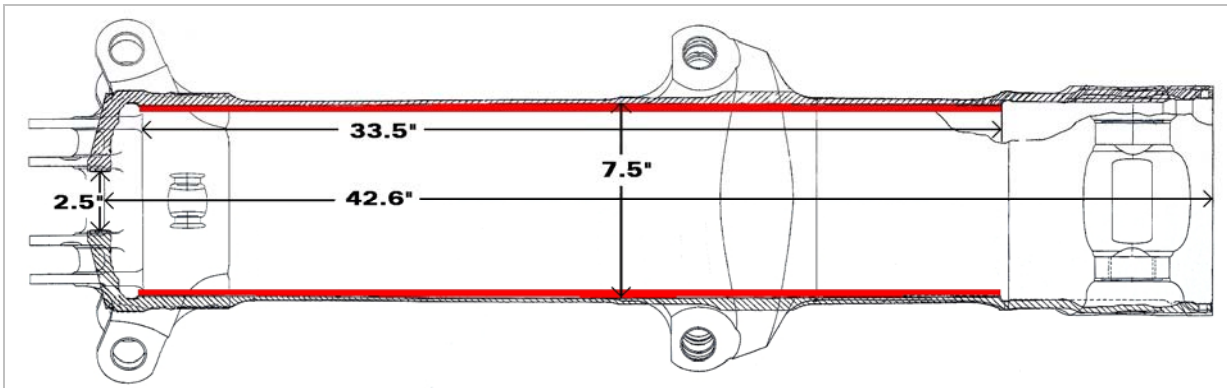



**Figure 5-9. P-3 main landing gear outer cylinder.**

In overhauling the P-3 the main landing gear outer cylinder is frequently ID chrome plated at NADEP JAX. This is currently done by using a standard chrome plating tank with an internal anode and fixturing arrangements.

This item would be fitted with hard cylindrical masking for the two ends and sprayed either upright on a rotary table or horizontally on a lathe. In order to reach the full length of the interior the gun would need to be equipped with a longer extension than is standard. The existence of a hole at the closed end the

component would make it easier to remove overspray, although attention would need to be paid to the proper design of gas jets to do so since overspray would tend to become trapped in that area.

Total coated area: 5.5 sq ft.

Plasma spray (F100 gun) coating time for 0.010" thickness: 1.04 hours

The spray time assumes 100% on-time and no spraying beyond the coated region. In reality the spray gun program would need to run the gun off the coated region and onto the masked area to ensure full coating, and it may be necessary to build in pauses to prevent overheating. Nevertheless the total spray time is likely not to exceed about 1.25 hours, compared with up to 24 hours for chrome plating.

## 5.7. Comparison with prior cost/benefit analyses

Two prior cost analyses have provided many of the costs for this report:

1. "Technology Transition Plan for W-2210 Project *HVOF as Hard Chrome Replacement (Task 5.1)*", D. Brock and D. Parker, October 2000[2]. This analysis was carried out to support the adoption of HVOF coatings to replace chrome plating on the 65% of the depot workload that involves OD coating. It draws on the some of the data developed in the JSF analysis (see below), which was done immediately before and was funded by Jean Hawkins of the JSF IPT, who is based at NADEP Jacksonville. The analysis was done for all three NADEPs, but our analysis simply extracts the information for NADEP Jacksonville.
2. "JSF Program Report CDRL A012", Parsons Engineering Science, Inc., January 1999. This analysis was carried out for the JSF program, to analyze the potential savings for the program that could be gained by replacing OD chrome with HVOF and ID chrome with plasma spray, as well as assessing non-chromated, low VOC e-coat in place of traditional spray painting for interior components. The data used in this report came from a variety of depot and commercial sources.

There are significant differences between some of the generic costs cited in the Parsons report (which were derived from various sources) and the actual costs used by NADEP Jacksonville. Since this analysis is specifically for NADEP Jacksonville, we have used Jacksonville's estimates.

Because of the way the numbers were analyzed in the NADEP Jacksonville analysis (item 1 above) it is not possible to extract the precise value used for each cost. For example, we cannot be sure exactly how the authors defined the number of overhauls per annum. However, it is possible to come very close to the input costs that were used. Using the data of Table 5-3 to Table 5-6, we find good agreement between the NAVAIR and Rowan estimates of the various value numbers (see Table 5-8). This shows that the two analysis methods are essentially equivalent and that we have correctly extracted the cost data from the NAVAIR analysis. Note that the Rowan values are consistently a little lower, which results from slightly higher estimates for the HVOF costs or slightly lower estimates for the EHC costs. (Note that in our ROI estimates Rowan utilizes the more common annualized ROI, rather than the ROI Ratio which cumulates the annualized values over the sampling period.)

**Table 5-8. Comparison of Jacksonville and Rowan value estimates.**

| Analysis result | Jacksonville | Rowan |
|---|---|---|
| Payback | 1.62 yr | 1.7 yr |
| IRR | 67% | 59% with depreciation<br>66% without depreciation |
| NPV over 12 yrs | $2,784,690 | $2,498,810 |
| ROI Ratio over 12 yrs | 6.27 | 7.0 |

# 6. Impact on readiness

The major reason for NADEP Jacksonville's desire to replace hard chrome with thermal spray is reduction of turnaround time. For example, the F404 engine Fan Drive Shaft takes 72 hours to repair with chrome plate, included masking, racking, waxing, chrome plating and baking. HVOF coating takes only 45 minutes, including grit blasting, racking and spraying.

Plasma spray also reduces turnaround time for the same reasons, as we see in the example below. The result of this is that plasma spray, like HVOF, has an inherent additional capacity. When necessary (e.g. when moving to a war footing) thermal spray capacity can be increased fourfold by moving from a single shift to 24/7 operation.

Faster processing of an item only has a direct economic impact if the item is on the critical path – i.e. if it is an item that the turnaround time of the total maintenance task for an aircraft. If it is not on the Critical Path then faster turnaround may simply mean that the completed item waits in storage until it can be assembled into the aircraft. By itself, therefore, ID plasma spraying of a few components (or even all components) will not necessarily affect overall turnaround time, if the change is made in isolation. However, depots are increasingly attempting to reduce turnaround time in order to return aircraft to the fleet quickly to maintain combat operations. **Thus faster processing turn time increases the number of combat-ready aircraft, and should be considered a readiness benefit for DoD, but not necessarily a cost benefit, especially for**

**the depot.**

The economic impact of reduced turnaround time includes

1. Reduced time-in-process, which reduces the capital tied up by in-process parts. For a commercial organization this reduces the carrying cost of operations by receiving payments more quickly. This benefit is included in the C-MAT model, but has not been included in this analysis as it is not relevant to a depot.
2. For DoD as a whole, shorter turnaround times for aircraft maintenance reduce the number of aircraft that must be purchased to maintain a given operational fleet size (since aircraft in depot maintenance are obviously not available for operations). For many aircraft this has no economic impact since all aircraft needed have already been purchased. Even where it does have an impact (as with new weapons systems such as F-22 and F-35) it has no economic impact for the depot, and thus does not affect the Cost-Benefit Analysis.

# 7. Risk Analysis

## 7.1. Technology risks

Since the technology itself is well defined, the materials and equipment are commercially available, and the ID plasma spray process is already in use for a variety of non-aerospace as well as one or two aircraft applications, the technology risk is low. The SERDP program has demonstrated that acceptable material can be sprayed onto the IDs of tubes down to 3".

Commercially available gun extensions permit spraying down to a depth of 24". As Section 5.6 clearly shows, however, spraying will need to be done at greater depths. There is no reason in principle why this cannot be done and manufacturers do supply non-standard extensions for this purpose. Electricity and plasma gas pose no problems. There should be no issue with transporting the powder to the gun, since this is done in a carrier gas, although the longer the tube the more likely it will be to clog. The flexibility of the gun is something of an issue, since the system must be rigid to avoid flexing and touching the side of the part being coating, or vibrating and varying the standoff distance. This is likely only to be an issue in small IDs where tolerances are tighter. It should not be a concern in larger components such as that shown in Section 5.6.

Heat and overspray removal are important issues for maintaining coating quality and avoiding any heat damage to the component. It is important to optimize the gas flow to blow overspray away from the coating region as well as to avoid overheating. This will need to be done as part of the overall process optimization.

Coatings such as WC-Co can be stripped using a benign Rochelle Salt electrochemical stripping solution. However, Ni or Cr-based composites such as $Cr_3C_2$-NiCr may require a Ni stripper, most of which are toxic.

Coatings can be ground and finished using standard commercial grinding wheels

and superfinishing tools.

## 7.2. Financial risks

The cost of the ID plasma spray technology is well known. There are two critical cost factors that are poorly known, as we have seen in Section 5:

1. Coating performance in service
2. Costs associated with any reduction in the OSHA PEL.

### 7.2.1. Coating performance

Coating performance is a function of coating material, deposition parameters and service conditions. Although some wear measurements indicate that plasma spray provides a performance enhancement, only service experience will show whether plasma sprayed components need reduced maintenance.

### 7.2.2. Costs associated with any new OSHA PEL

There are two parts to this uncertainty:

1. The final PEL number. A PEL of 1 $\mu g\ m^{-3}$ appears likely, but is by no means assured. The cost of compliance will depend strongly on the final rule, which will not be known until 2006. The PEL will be unlikely to be adopted at the very low limit suggested if it can be clearly demonstrated by the plating industry to have an unacceptably high cost (such as doubling the cost of chrome plating or making welding unreasonably difficult). Yet it is this very large potential cost impact that would make plasma spray replacement of ID chrome a cost-effective proposition.
2. Cost of compliance with the lower PEL. The assessment of these costs, based on the Navy/Industry Taskgroup study, is very crude and general. The full cost of compliance will need to be fully and accurately assessed, using NADEP Jacksonville’s specific costs and potential worker exposures rather than numbers that apply generally to a broad range of depots and commercial shipyards.

## 7.3. Business risks

There are no business risks apart from those covered in Section 7.2 above. The technology is readily available using commercial equipment, gases and powders, and there are no licensing issues since the technology is not proprietary.

All of the equipment and materials are available from multiple commercial sources.

## 7.4. Other risks

We are not aware of any other significant risks.

# 8. Environmental Assessment

If ID plasma spray is used for ID chrome replacement in conjunction with HVOF

for OD chrome replacement, this will enable NADEP JAX to totally eliminate chrome plating with all of its waste streams. The totals shown in Table 8-1 are for the 35% of the workload attributable to ID chrome plating only.

**Table 8-1. Hazardous material reduction.**

| | Current technology | | New Technology | |
|---|---|---|---|---|
| | amount | units | amount | units |
| **On-site TRI inventory** | | | | |
| $Cr^{6+}$ solution | 1,085 | gal | 0 | |
| | | | | |
| **TRI materials** | | | | |
| $Cr^{6+}$ waste | 933 | lb | 0 | |
| $Cr^{6+}$ contaminated wastewater | 17,279 | gal | 0 | |
| Co | 0 | lb | 208 | lb |
| | | | | |
| **Other Hazmats** | | | | |
| Grinding waste, Cr and Pb contaminated sludge, maskant etc. | Not known | | | |

Note that Co, used in WC-Co plasma spray, is a TRI chemical that must be reported if >1lb/yr is released into the environment. This is not a material present in chrome plating wastes. However, it is in metallic form and is far less toxic than hexavalent chrome[6]. Unlike Cr, Co is not a RCRA reportable material.

The weight of other Cr-contaminated wastes, especially wax maskant, are an order of magnitude higher than waste from the plating tanks and mist eliminators, according to an analysis by Parsons[3]. However, no information is available on the amount of such wastes from plating operations at NADEP JAX.

**However, the primary environmental reduction comes from the fact that ID plasma spray permits the final elimination of chrome plating, with all its wastes and air emissions, from the depot.**

# 9. Recommendations and Conclusions

ID Plasma Spray is a technology that is technically and economically feasible and a good fit in the depot environment. Because of its implementation cost, It will not be a cost reduction unless the OSHA PEL is reduced to the level of 1μg $m^{-1}$ and the cost of this reduction to the depot comes close to doubling the cost of chrome plate. The cost of ID plasma spray is comparable with chrome plating, provided equipment is used that has a high enough deposition rate. It may be capable of reducing wear and hence increasing the overhaul cycle on some components, although rig and field testing will be required to validate any performance improvement.

At this point there is little need for extensive additional materials testing. The

technology is sufficiently mature that it can be applied to components immediately for rig and service testing, but doing so on most components of importance to NADEP JAX is likely to require the use of equipment with longer ID spray extensions than are currently available for standard commercial use.

**The primary value of the technology is as a logical companion technology to HVOF that permits a single technology (chrome plating) to be replaced by another single technology (thermal spray – HVOF for ODs and plasma spray for IDs) whose overall performance is better and whose turnaround time is significantly less.**

# 10. TRL Definitions

The original Technology Readiness Level definitions were developed by NASA and formalized

| TRL | Definition |
|---|---|
| 1 | Basic scientific principles only known and reported |
| 2 | Technology concept/application formulated, potential benefits identified |
| 3 | Proof-of-concept demonstrated in lab |
| 4 | Primary performance parameters – representative parts or specimens lab tested (no show stoppers) |
| 5 | Validation – lab specimen performance tests, relevant exposure environment tests (e.g. beach or shipboard corrosion) and producibility demonstration |
| 6 | Rig testing – actual or simulated components in real or closely simulated test rig |
| 7 | Flight testing – actual components |
| 8 | Qualification – process/product has passed qualification tests |
| 9 | Operational testing – actual operating environment, fleet operating experience gained |

by the GAO[7], and are not directly relevant to most materials technologies. We have adapted them to create the simplified TRL definitions shown in the table.

# References

[1] HCAT Landing Gear Joint Test Protocol, September 1999. Available on HCAT web site.

[2] "Technology Transition Plan for W-2210 Project *HVOF as Hard Chrome Replacement (Task 5.1)*", D. Brock and D. Parker, October 2000 (Distribution Statement A unlimited).

[3] "JSF Program Report CDRL A012", Parsons Engineering Science, Inc., January 1999. Contract # F47408-95-D-0727, Delivery Order 0027.

[4] "Hex Cr PEL Standard - OSHA's Expedited Rulemaking", Kathryn McMahon-Lohrer, AESF Jan 2004. Available on HCAT web site.

[5] "Impact Of Anticipated OSHA Hexavalent Chromium Worker Exposure Standard On Navy Manufacturing And Repair Operations", submitted to OSHA for use in preparing draft standards, October 1995. Available on HCAT web site.

[6] "Cobalt Industrial and Environmental Health Risk Assessment: A Case Study", C. Tomljanovic, et al.(2003). Funded by ESTCP. Available on HCAT web site.

[7] "Best Practices – Better Management of Technology Development Can Improve Weapons System Outcomes", General Accounting Office, GAO-NSIAD-99-162 (June 1999).

# Appendix 4. THREE TEAM MEETING REPORT – ID COATING TECHNOLOGY COMPARISON

A meeting of all three teams involved in SERDP-funded ID coating development was held in conjunction with the HCAT meeting in San Diego, April 1, 2003.

## 1. Attendees

About 25 attendees were present (a quarter of the total HCAT attendees), including the members of the three ID teams and people from Boeing, Lockheed, Honeywell Engines Systems & Services, Textron Actuators, Praxair, Sulzer Metco, and NADEP Jacksonville.

## 2. Presentations

The meeting was designed to be informal to allow for maximum discussion and transfer of information among the different team members and the potential users.

The following is drawn from the presentations, from discussions at this meeting and from other discussions during the course of the HCAT meeting.

### 2.1. Nanophase electroplating – Doug Lee, Integran

This program is nearing completion, with additional fatigue and embrittlement data to be taken.

The method uses pulse electroplating to deposit a Co alloy. The best data have been obtained with Co-P, with P of 2-5 wt%. Anodes can be either consumable (Co chips) or inert (graphite). The method can plate the ID sides and bottom simultaneously provided the anode is properly placed.

**Process capabilities**:

- Diameter – No inherent maximum diameter. No minimum diameter has been tested, but Ni has been coated using the same technology into diameters as small a diameter as ½”. This is a wide enough range for any landing gear, actuator, or linkage pin.
- Length – No inherent limitation
- Thickness – Can be thin (<0.0005”) to thick (>0.020”). This is the range in which Cr is used, from thin dense chrome to build-up chrome.
- Rate – Because it is efficient, the rate is 0.003” – 0.006” per hour. This compares with 0.0005” – 0.001” per hour for hard chrome.
- Area – Maximum area not known. Area would be limited by the maximum pulsed current capability of the power supply. No specific limits are known.
- Temperature – The method does not cause heating. However, the hardness is lowest as-

deposited and can be improved by heat treating. A 350°F heat treat (used for embrittlement relief) has no effect and even 450°F only gives about a 50HV hardness increase. Thus for most airframe applications coating hardness will be the maximum as-deposited (about 800HV).

- Ductility – 2-7% elongation (vs <1% for hard chrome). Ductility falls and hardness rises with increased P content.
- Waste treatment – Use a closed-loop system for water recovery and can sell discarded solution chemicals.
- Hardness – 600-700HV as-deposited, 1,000-1,200HV after 400°C heat treat, compared with 800-1,200HV for hard chrome (although hard chrome can be as low as 700HV).
- Residual stress – 10-15ksi tensile. This is likely to cause a fatigue debit, especially at greater thickness. Stress can probably be adjusted via solution chemistry and deposition conditions.
- Porosity – No data available, but probably very low (probably <1%).

**Process limitations**:

- Hardness – Hardness is lower than for hard chrome, and for most high strength steels and other structural alloys it cannot be raised by heat treating since heat treating temperatures are too high.

**Performance**:

- Abrasive wear – About 10x higher wear rate than EHC because of lower hardness.
- Sliding wear – About 50% of EHC because of less adhesion, presumably better lubricity. For most ID applications sliding wear is most important. However, when foreign particles or debris become trapped in seals, etc., abrasive wear would be more important.
- Salt fog corrosion – Better than EHC.
- Hydrogen embrittlement – Looks good, but still under evaluation.
- Fatigue – Shows debit from uncoated material. Comparison needed with EHC on same material as UTS of the substrate was below specification.

## 2.2. ESD – Roger Johnson, Battelle

This work is now complete apart from a few results still to come in from AFRL.

ElectroSpark Deposition is a microarc overlay coating process – essentially a microscopic welding technique. It can be done manually or using automatic control. A wide variety of metals and some cermets can be used as the coating material. As well as evaluating different ESD overlay materials, the project has concentrated on process control, including pulse shape and contact load for both automatic and manual deposition.

**Process capabilities**:

- Can be hand-held and equipment is small, inexpensive and highly portable. This makes it an ideal method for *in-situ* repairs in tight spaces such as shipboard.
- Training – Method is easy to learn. Since some Navy enlisted men are taught welding

and similar repair methods, this ought to be able to be done by similar personnel after a limited training period.

- Diameter – No inherent maximum diameter, but economics dictates small diameters and best for repair. Has been done in diameters as small as ¼”. This is small enough for any linkage pin. The ability to reach into small and difficult-to-access areas makes it ideal for repair.
- Length – No inherent limitation
- Thickness – Typically 0.001”-0.010”, or thicker for very localized build-up. Below about 0.001” coatings tend not to be continuous.
- Rate – Very low (typically 0.1-1 gm/hour). This makes it unsuitable for cost-effective coating of large areas.
- Area – Area is limited by the low deposition rate.
- Temperature – The method does not cause heating, except very locally. Typical Heat Affected Zone (HAZ) thickness is a few microns. No component warpage.
- Ductility – Not known.
- Hardness – 700-750HV for Stellite 6 (vs. 400HV for bulk); 575-600 for Stellite 21 (vs. 300HV for bulk). Note that, in common with nanophase electroplating, ESD coatings have nano-sized grains and so have Hall-Petch hardening, making them much harder than bulk materials.
- Residual stress – Tensile. Hardfacing coatings, such as carbides, tend to be cracked as-deposited, with cracking increasing with thickness. Hard Stellites are often cracked above about 0.003”, whereas softer Stellites (e.g. Stellite 21) and other softer coatings are usually not cracked, even up to 0.010”.
- Porosity – Depends on materials and parameters. Thin coatings (<0.002”) tend to be low porosity, but porosity tends to increase with thickness.
- Waste treatment – Very small waste volume (small volume of powder produced from arcs <1gm/day). Masks are not generally required as dust generation is so low. Dust or fume generation could be a problem with some ESD materials or substrates (e.g. repair of Cd plating or chromated surfaces), but should be amenable to use of a simple mask. (In general ESD is not likely to be used for repair of these types of materials.)

**Process limitations**:

- Deposition rate – The very low deposition rate makes this method unsuitable for large area repairs.
- Residual stress – Tensile stress makes it difficult to make coatings without cracks, and appears to create a significant fatigue debit.

**Performance**:

- Abrasive wear – No data. However, hardness of 700-750 for Stellite 6 should give similar abrasion resistance to EHC.
- Sliding wear – Very low coating wear for Stellites, carbides. TiAl-$TiB_2$ shows higher wear.
- Corrosion – Data not yet available

- Hydrogen embrittlement – None expected since the method is dry.
- Fatigue – Stellite 21 has about same fatigue debit as EHC. (Early data were very poor due to the process being optimized for maximum deposition rate, which gave high tensile stress and large HAZ.).

## 2.3. Plasma spray – Keith Legg, Rowan

This program is in progress with the final report scheduled for early 2004.

HVOF cannot be done inside IDs since the gun and standoff are too large to fit into most IDs. The ID plasma spray process uses a miniature plasma spray gun that heats and sprays powder through a plasma plume. Several miniature guns have been tested from Praxair and Sulzer Metco.

Many powders have been tested, and we have settled on 4-6 final powders for detailed evaluation:

- Tribaloy 400
- WC-12Co
- WC-Co in self fluxing matrix – different powders from Praxair and Sulzer Metco.
- Two additional powders are under initial evaluation and may be included in detailed testing if results warrant.

Performance data are still being obtained. However, based on the work thus far the process has the following capabilities and limitations.

**Process capabilities**:

- Diameter – No inherent maximum diameter. Minimum diameter 2.5 – 3" depending on powder and quality desired. This limitation is primarily imposed by the need for an adequate standoff (gun-surface distance). This is small enough for any landing gear outer cylinder, most utility actuators, and some dampers and flight surface actuators. It is too large for many flight surface actuators as well as for linkage pins.
- Length – No inherent limitation. Standard lengths are up to 24", but length could be increased as needed. Limitation is the stability of the gun, which will move around more easily at too great a length.
- Thickness – Minimum thickness approximately 0.001" for a reliable continuous coating. Can be very thick (>0.020"). This is the range in which EHC is used, but it is too thick for a thin dense chrome alternative.
- Rate – Typical rates are >1kg per hour – faster than most other processes. This compares with 0.0005" – 0.001" per hour for hard chrome.
- Area – No limit to the maximum area since the gun is traversed over the area and coating rates are high.
- Temperature – The method does cause heating, which is a more serious problem in IDs than in ODs where cooling is easier. The coating is used as-sprayed – no heat treat is required.
- Ductility – Similar to EHC (typically <1.5%). However, Tribaloy shows no sign of cracking using acoustic emission in 4-point bending. Other coatings will spall, as HVOF

does, if highly stressed tensile and then compressive.

- Porosity – Typically 2-10% but not interconnected. (HVOF is generally <1%.)
- Overspray – In IDs powder that does not become properly heated and therefore does not stick to the substrate remains close to the surface and can be incorporated, forming a poor quality coating. This dust must be removed by proper aiming of a gas jet. Work on *in-situ* overspray measurement and minimization is continuing.
- Waste treatment – Overspray is drawn out of the booth and caught in standard bag house dust filters.
- Hardness – 650-850HV for the carbides (significantly lower than HVOF carbides); 400-500HV for Tribaloy. However, Tribaloy tends to be more lubricious.
- Residual stress – neutral to slightly tensile. Unlike HVOF coatings, which are almost always compressive because of the high velocity and self-peening, plasma spray coatings are almost always tensile, which is likely to give a fatigue debit.

**Process limitations**:

- Diameter – Minimum diameter cannot be lower than 2.5”. the new Sulzer Metco F300 gun is being tested since it is smaller than others, but it is doubtful that, with adequate standoff, the diameter will below 2” – still too high for most pins and some of the smaller actuators.
- Surface finish – The finish is rough as-deposited, meaning that plasma spray coatings will have to be ground.
- Heat – Process heating can be kept down so as not to be a problem for most materials. However, some heat-sensitive materials could be problematic.

**Performance**:

- Abrasive wear – About the same as EHC for the harder carbides, higher wear for softer materials, and particularly high wear for Tribaloy.
- Sliding wear – About the same as EHC, but Tribaloy somewhat worse. Tends not to pick up material from counterface as chrome does.
- Corrosion – Work just getting under way, starting with electrochemical testing.
- Hydrogen embrittlement – Not done, as it is know that thermal spray does not cause embrittlement.
- Fatigue – Testing just getting under way.
- Coating integrity – Spalls at high load under reversed stress. However, Tribaloy shows no sign of cracking or spalling.

# 3. Discussion

Most of the discussion took place during the course of the presentations. Additional discussions between various people took place at other times during the HCAT meeting, including the use of ESD for repair and the use of nanophase electroplate as a thin dense chrome alternative.

Robert Trice (Lockheed JSF) mentioned that SO2 salt fog tests will be needed for qualification since they are even being required for electronics hardware.

ID Plasma spray is now being qualified for both CH-53 and CH-60 blade dampers. There have been some test issues that require resolution. ESD is now being validated as a local repair technology (a dry analog of brush plating) under ESTCP funding. Nanophase electroplate is being proposed for ID and thin dense chrome replacement.

During the ID meeting we discussed the relative capabilities and uses for the three technologies as summarized in the following table. This table was modified from Keith's presentation.

| Application | Nano-Co | Plasma spray | ESD |
|---|---|---|---|
| Major strengths | Smooth, bath drop-in | Wear resistant, low waste | Repair, portable, difficult-to-reach areas |
| Large – LG outer cylinder | Good – scale up needed | Fast – diameter OK, any length can be provided | Very slow – not suitable |
| Short - dampers | Good – no scale up needed | Good – rapid, efficient | Good for repair |
| Small - pins | Can coat down to ½" ID | Not usable | Good, efficient, no masking |
| Thick build | Quite good – faster than Cr | Good – high rate | Not suitable, except small area repair |
| Thin dense or flash Cr | Good – efficient, smooth, nodular | Not suitable – too thick, rough | Not suitable – too rough |
| Local repair | Brush plate | Can be done | Very good, can be hand-held, transportable |

# Appendix 5. ESOH Issues for Plasma Spray

An analysis was made of the potential ESOH issues associated with plasma spray of Co containing materials.

# SAFETY, HEALTH AND HAZARDOUS WASTE ISSUES OF OVERSPRAY IN THERMAL SPRAY

**SERDP Project #1151**

**Keith Legg, Rowan Technology Group**

**Bruce Sartwell, Naval Research Laboratory**

**Jean-Gabriel Legoux, National Research Council of Canada**

**March 16, 2001**

# EXECUTIVE SUMMARY

This white paper summarizes the available information on thermal spray Environmental Safety and Health (ESH) issues concerning particle overspray. As well as a summary document, this report incorporates as appendices various ESH documents on the toxicology of WC, Co, and Cr.

There are some ESH issues associated with thermally sprayed WC-Co and WC-CoCr based on the toxicology of the materials, and general issues related to fine powders, but they do not pose an operator hazard or cause environmental problems in a properly designed spray booth and properly controlled process. Whenever the operator may be exposed to powders (such as when handling the thermal spray powder itself or when setting up the equipment with the gun running) he should be protected with an OSHA-approved mask. Spraying takes place in a booth isolated from the operator, and the spray booth is designed to remove particles and gas very rapidly. None of the materials (including metallic Co and Cr) is a known carcinogen, and metal vapors (which are major concerns in welding operations) are not a serious issue for thermal spray. The thermal spray process should produce little vapor if the process is properly controlled, and any vapor produced should be rapidly swept from the booth by the air handling system.

The main concern is overspray – i.e. particles that bounce off the substrate or are sprayed into the air – that becomes deposited in dead areas in the booth or on the fixturing and is not removed by the air handling system. There is increasing concern over particulate matter under 2.5μm (PM-2.5), which is believed to be a more serious problem than larger (PM-10) particles that have traditionally been regulated, and which may not be trapped by standard filter masks. At this point the health effects of such particles are poorly understood or documented, and the few studies that have been done are primarily concerned with diesel engine emissions. However, it is important that we avoid operator exposure to or emission of these particulates into the atmosphere.

Most thermal spray powders are in the 20 – 100 μm range, and do not pose a serious danger because they will be trapped by standard filter masks. No problems have been reported with the use of these powders by the thermal spray industry. We believe that the only serious risk is with spraying nanoagglomerate particles. Although these particles are 20μm or more in diameter, significant numbers of PM-2.5 particles might be produced when spraying them, since the spray process will tend to break up the loose nanoagglomerates into fines that could include particles with a size distribution down to a few nanometers.

Since there is no information in the literature on size distributions of such particles in the thermal spray process, we will be carrying out spray booth measurements at NRC in the April/May time frame.

# TABLE OF CONTENTS

# 1. Introduction

The primary Environmental Safety and Health (ESH) issues with thermal spray are associated with the overspray material – that is particles that miss the substrate, fail to stick to the substrate and bounce off into the spray booth, but are not swept into the dust collectors. (In a few materials the overspray is modified by the spray process and becomes an ESH problem, requiring the collected overspray to be disposed of as toxic waste. This is the case for $Cr_2O_3$ plasma spray, since some of the chromium oxide can be further oxidized to the hexavalent state, but does not appear to be a problem for materials containing metallic Cr.)

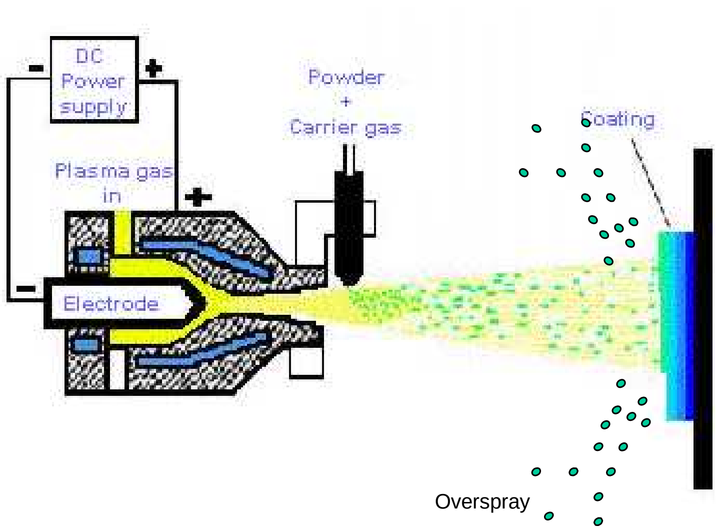



**Figure 1. Plasma spray gun and overspray.**

**Figure 2. Thermal spray dust collector.**

Figure 1 shows a typical plasma spray gun. Powder is injected into the high velocity gas stream at the output of the gun nozzle. Most of the particles are heated and accelerated so that they become properly incorporated into the growing coating. However, some particles do not properly enter the gas stream, or fail to be adequately heated and accelerated, and bounce off the substrate. Furthermore, to ensure uniform coating across the entire component, the gun must be swept beyond the edge of the substrate, often spraying heated powder into the air. The total loss due to these two mechanisms is usually in the region of 20-50% - i.e. up to half the powder can be lost.

The spray booth is equipped with a high capacity air handling system to remove overspray and heat from the spray booth very efficiently and quickly. Particles that do not become incorporated into the coating are swept into the air handling system and caught in a bag house (Figure 2). A typical cellulose filter used in these collectors is 99.99% effective for particles down to about 0.5µm.

Because overspray puts powder into the booth, and some is inevitably left in dead spots or otherwise trapped in the booth, it is a potential ESH issue for booth operators. The importance of overspray depends on the toxicity of the material being sprayed and the size of the particles.

# 2. WC-Co and WC-CoCr ESH data

**Summary of terms**

| | |
|---|---|
| OSH | Occupational safety and health |
| pel | Permissible exposure limit |
| REL | Recommended exposure limit |
| TWA | Time weighted average |
| LD50 | 50% probable lethal dose |
| PM-2.5 | Particulate matter 2.5µm or less in size |
| PM-10 | Particulate matter 10µm or less in size |
| IARC | International Agency for Research on Cancer |

Toxicity and ESH data are provided in documents on the Material Options website, which are in Acrobat (PDF) format, and can be accessed at:

http://www.materialoptions.com/w2g/cgi/kmcgi.exe?O=DIR0000000OLX&V=0

**Document 1. MSDS data for WC thermal spray powder.**

**Document 2. Toxicity of Cobalt.**

**Document 3. Toxicity of Chromium.**

**Document 4. IARC study of Co and Co compounds.**

**Document 5. IARC study of Cr and Cr compounds.**

**Document 6. Public health and toxic particles.**

(Note: This paper is mostly concerned with diesel emissions and toxic particles, but it does provide some information on current thinking about particulates in general.)

The overall conclusion is that these materials are not particularly hazardous, and they are not known carcinogens, although, as with all metal powder and fumes, breathing them (especially over prolonged periods) should be avoided. The only toxicity issues are related to the metal matrix, not the WC, and most of the known toxicity issues are related to welding, where metal vapors are produced in close proximity to the operator. In plasma spray, the operator is usually in a booth separated from the spray process, and high speed air handling is designed to sweep out dust and vapors very quickly. In the thermal spray process metal vapor production should be very small, unless the process is poorly controlled so that the powder is grossly overheated.

Toxicity of these materials may be summarized as follows:

- Exposure to WC-Co dust and fumes
    - Short term exposure to powder and spray arc fumes may result in irritation of the nose, throat, eyes and skin.

- Chronic overexposure to powder and spray arc fumes may result in bronchial asthma, lung fibrosis or pneumoconiosis.

- Exposure to Co dust and fumes
  - OSHA pel for Co (8hr TWA) = 0.1 mg(Co)/$m^3$
  - NIOSH 10 hr TWA REL for Co = 0.05 mg(Co)/$m^3$
  - WC-17Co weld powder – Fire, acute health, and contact hazards are all labeled as slight
  - For Cobalt the LD50 lethal dose is 6.2 gm/kg of body weight (about 400 gm for a 150 lb operator)
  - Co is an IARC Group 2B material, which means that “The agent (mixture) is possibly carcinogenic to humans”.
    - Co is tumorigenic in laboratory animals (mostly at site of application)
    - The evidence for human carcenogenicity is inadequate (Note: Medical prosthetic implants, such as hips, are usually made of CoCr alloys.)
- Exposure to metallic Cr dust and fumes is far less serious an issue than exposure to hexavalent chrome
  - OSHA pel for Cr (8hr TWA) = 1 mg(Cr)/$m^3$
  - NIOSH 10 hr TWA REL for Cr = 0.5 mg(Cr)/$m^3$
  - For Chromium the LD50 lethal dose is 27.5 mg/kg of body weight (about 4 gm for a 150 lb operator)
  - Note: The pel and REL for Cr are 10x those for Co, but the LD50 dose for Cr is 0.4% that for Co (i.e. the exposure limits for Cr are lower, but the lethality is higher).
  - Both Cr and Cr(III) are IARC Group 3 materials, which means that “The agent (mixture or exposure circumstance) is not classifiable as to its carcinogenicity to humans.”

# 3. Overspray ESH issues

Because it has traveled through the gun and the air, overspray powder can be different in size and chemistry from the starting powder. Most powders are agglomerates of smaller particles that can break up on impact or in the plasma to create fines that are much smaller than the original powder. They can also become oxidized or reduced to create different chemistry.

Spray booths are designed to have a very high air flow across the spray area, which is intended to entrain the overspray and catch it in dust collecting filters in a bag house (usually outside the building). In a properly-designed booth the air volume should clear the air of particulates and fumes within seconds of the end of a spray run. However, some powder inevitably becomes trapped in dead zones in the booth, and the operator may therefore be exposed when working in the booth. Operators may also be exposed when loading and unloading powder feeders and when setting up work in the booth (for which the operator must occasionally enter the booth with the gun running).

Changes in chemistry are not generally a concern, and is only known to be a problem in the spraying of $Cr_2O_3$ (see above).

## 3.1. Standard particles

When working with standard thermal spray materials, especially when using powders that contain hazardous materials, operators should always be equipped with OSHA-approved 1µm or 5µm filter masks, which will protect against spray powders and their fines. Typical powder sizes for thermal spray are 20-100µm in size, and are easily caught in filter masks and dust collectors. Historically thermal spray operations have not been found to create operator exposure or significant air emissions within or outside the plant. Although WC-CoCr contains cobalt and chromium, they are in metallic form, and as noted above this is not a serious toxicological issue.

For this reason, we do not believe that under normal spray conditions the thermal spray process exposes operators to dangerous levels of particulates or fumes, provided the booth is properly designed, the operator does not remain in the booth during spraying, and proper respirators are used whenever exposure might be likely (including during handling of powders and working in the booth).

## 3.2. Nanoagglomerate spray

We believe that the main area of ESH concern in overspray would be in the use of nanoagglomerates, which are used in nanoparticle thermal spray. The SERDP program includes this approach because it may offer superior properties and the ability to spray smaller diameters. Nanoagglomerates are somewhat loose agglomerates of nanometer-size particles (Figure 3). The agglomerates themselves do not pose a problem since they are typically 20µm in diameter. However, during spraying the agglomerates could break up into many small particles that are sub-2.5µm in size (designated PM-2.5), which has been found to be a particularly hazardous size range. Many of these break-up particles could be in the PM-2.5 range. The individual nanoparticles themselves are too small to be trapped by filters, and may pose a health risk. Particles of nanometer size are not generally considered to be a health problem, provided the materials themselves are not toxic, but since it is only recently that these types of nonomaterials have come into use, an ESH risk cannot be completely discounted.

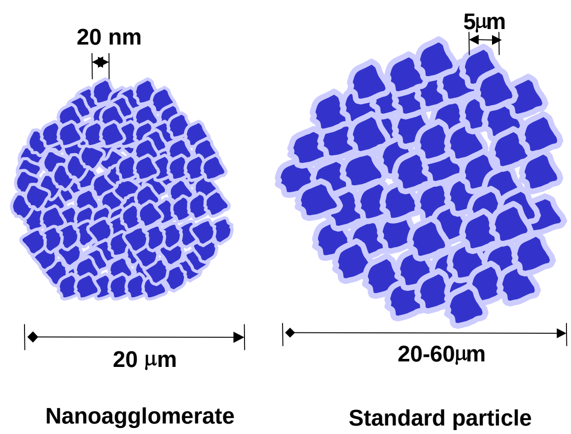



**Figure3. Standard and nanoagglomerate thermal spray powders.**

The health effects of PM-2.5 are not well-documented or understood[3], and most studies in this area are related to diesel engine emissions. However, PM-2.5 particulates are generally believed to be a more serious concern than PM-10 (10µm particles) because the smaller particles can penetrate deeper into the lungs and alveoli. In 1997 EPA updated the general Air Quality Standards for Ozone and Particulate Matter, instituting standards for the first time for outdoor air for PM-2.5 particulates because of concern over respiratory effects of fine particles, which can

3 http://www.house.gov/science/epa_report_6-25.html

cause asthma, bronchitis, and other respiratory problems. (On May 14, 1999, the U.S. Court of Appeals for the District of Columbia Circuit blocked EPA's authority to implement the new 8-hour ozone standard and the PM-2.5 standard, an action which is under appeal.) While the EPA actions do not affect plasma spraying directly, they do point to concerns over PM-2.5 ESH issues that are likely to lead eventually to more stringent workplace standards.

## 3.3. Analysis to be done in this program

Although nanoparticle spray has been under development for two or three years, there is no ESH information in the literature on nanoparticle overspray or the particulate matter to which thermal spray operators might be exposed when using nanoparticle sprays. For this reason, the SERDP ID program will be carrying out an analysis of overspray particulate concentrations when spraying nanoagglomerate and standard particles. The evaluation will include particle concentration and size analysis for a spray booth with and without air handling, to determine particle sizes and potential operator exposures using standard personnel air monitoring equipment. This work is to be done at NRC, Montreal, and is planned for the April/May 2001 time frame.

# Appendix 6. THERMAL SPRAY OF NANOMATERIALS

A survey of published data and conclusions on plasma spray of nanomaterials have been assembled by Salim Bouaricha of NRC-IMI. This document is available at http://207.152.96.170/w2g/cgi/kmcgi.exe?O=REV0000000M0T&V=44/Salim%20Bouaricha%20Surftec%20November%202003%20mod_V1.PDF .

# Appendix 7. NEW DEVELOPMENTS

**Miniature ID plasma gun:** Under ONR funding Smuel Eidelman of SAIC has developed a pulse (detonation) thermal spray method built on a space thruster design. The system is computerized and uses high speed valves to inject the fuel, oxygen, and powder in the correct sequence so that the powder is driven out at high speed with the hot gas plume from the fuel/oxygen explosion. This makes it a form of miniaturized detonation gun, which is an HVOF deposition method. The system has been quite extensively modeled and appears capable of achieving high particle velocities, especially for nanoparticles.

The gun itself is very small (typically 1/4”-3/8” diameter), and when using nanoparticle feedstock it can deposit onto interior walls using a bent tube as a “barrel”, with a very small standoff distance. This allows the gun to coat inside an ID of <1”. We have visited Dr. Eidelman’s laboratory and discussed the technology with him. He also spoke at the HCAT meeting at KSC in November 2003. Spray rates appear to be quite high and coating quality good, with low porosity, although as with the plasma spray, the hardness is somewhat low compared with standard OD coatings. No detailed data are available. We had hoped to test some of these coatings under this program, but the cost of development for the production of test specimens was too high. Coatings made by this technology are under evaluation by Boeing.

This technology appears to be essentially similar to (although much smaller than) a miniaturized version of the High Frequency Pulse Detonation technology being marketed by Turbodetco in Spain.

**ID HVOF gun:** In 2006 Northwest Mettech (www.mettech.com) announced the development of a new HVOF gun for spraying IDs. This gun is said to be capable of spraying IDs down to 90mm (about 4”) diameter, to a depth limited essentially by the fixture on which the gun is placed. With a spray rate of 60 gm/min and a deposition efficiency of about 50%, the deposition rate should be equivalent to that of the F100 plasma spray gun. Thus the economics of this system should be essentially the same as for the F100. However, because this is an HVOF gun, the coating quality and performance should be essentially the same as other HVOF coatings, providing a coating life significantly longer than that of hard chrome.

Since this ID HVOF gun is new there are likely to be few vendors able to apply coatings with it. However, any organization that currently carries out its own HVOF coating deposition could purchase the equipment.